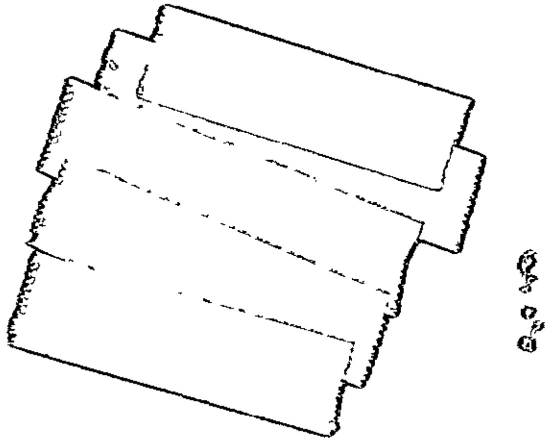
DESIGN OF A VIDEO SYSTEM PROVIDING OPTIMAL VISUAL INFORMATION FOR CONTROLLING PAYLOAD AND EXPERIMENT OPERATIONS WITH TELEVISION

NASA CR-
144637

(NASA-CR-144637) DESIGN OF A VIDEO SYSTEM PROVIDING OPTIMAL VISUAL INFORMATION FOR CONTROLLING PAYLOAD AND EXPERIMENT OPERATIONS WITH TELEVISION Final Report (Radio Corp. of America) [illegible] N76-14337
Unclas
G3/32 05649

FINAL REPORT

PREPARED FOR:
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
JOHNSON SPACE CENTER
HOUSTON, TEXAS 77058



CONTRACT NO. NAS 9-14266
ISSUED: JUNE 30, 1975

RCA GOVERNMENT AND COMMERCIAL SYSTEMS
ASTRO-ELECTRONICS DIVISION
PRINCETON, NEW JERSEY 08540

112 p.

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I. INTRODUCTION

This program has consisted of an investigation of remote operations and of the characteristics of television systems that will lead to efficient performance and utilization of equipment. The objectives are to characterize the video systems based on analysis and simulation testing, to make recommendations as to the preferred system, or systems, and to deliver in breadboard form the essential elements of such a system together with system specifications

This Final Report summarizes the first and second phases and covers the third phase of a three phase program which consists of:

<u>PHASE 1</u>: <u>Analysis of the Visual Process</u> - This phase covers the study and analysis of visual tasks, establishment of prototype scenes, identification of critical scene parameters, development of simulation test objectives, a review of potential stereo TV systems, design and procurement of the breadboard TV equipment.

<u>PHASE 2</u>: <u>Simulation Testing</u> - This covers final definition of simulation tests, generation of test procedures, breadboard equipment checkout, simulation tests, and test data evaluation.

<u>PHASE 3</u>: <u>System Selection and Specification</u> - This includes appropriate weighting of simulation test results, system ranking, system burden analysis, evaluation of system tradeoffs, and final system selection and specification.

II. SUMMARY

This Final Report summarizes the first 2 phases and covers the third and concluding phase of a twelve month program which resulted in the design of a television system for remote operations. The effort performed by RCA-AED and subcontractor, Perceptronics, has consisted of the design of a set of simplified simulation tasks, design of apparatus and breadboard TV equipment for task performance, and the implementation of a number of simulation tests. Performance measurements were made under controlled conditions and the results analyzed to permit evaluation of the relative merits (effectivity) of various TV systems.

Burden factors were subsequently generated for each TV system to permit tradeoff evaluation of system characteristics against performance. Conclusions may be drawn, based on this effort, to permit the selection of the particular TV system offering the desired effectivity/burden balance.

For the general remote operation mission, the 2-view system is recommended. This system is characterized and the corresponding equipment specifications were generated. Sections III through VII summarize the first phase effort previously reported in the First Engineering Design Report. Sections III and IV are concerned with the operator function and visual function analysis. Section V reviews the selection rationale and describes the scene paramters. Design aspects of the simulation and experiments are summarized in Sections VI and VIII, respectively. Section VI, covering apparatus and equipment, summarizes the effort and references the documentation containing engineering details.

Test results are given and discussed in Section IX. The statistical analysis process is presented and the performance differences among systems are discussed. Additional tests and observation, apart from the formal test series, are described.

The test results, are converted into system effectivity by means of scaled rankings and presented in Section X. Burden analysis, comparing non-performance characteristics of the system is treated and a mechanism to enable comparison and trade-offs between performance and burdens is described.

Conclusions leading to recommendation of the 2-view system is contained in Section XI. The system is characterized in this section and equipment specifications are presented in Appendix C.

Two other appendicies containing supplementary detail are also included in this report. Appendix A contains the first test series input data for the 2-repetition means. Appendix B contains by-task graphs for the individual performance measures of the first test series

III. OPERATOR FUNCTION ANALYSIS

A. Introduction

The starting point for the Phase I effort consisted of a review and classification of operator tasks for remote observations. The primary emphasis of this effort was directed toward reducing the array of tasks to a representative grouping to permit a simulation design of manageable proportions. The results of this work were described in Section III of the First Engineering Report; the following paragraphs contain a summary of that material.

B. Task Categories

A set of typical operations and their associated visual functions were compiled, allowing for classification of the tasks into categories. Two dimensions of classification appear dominant - element relationship and work volume. Element relationship refers to the configuration between several objects or between the object and manipulator end effectors, while work volume is concerned with the extent of the physical working envelope.

The three levels of element relationship and the major visual functions are:

1) Observation of Object

- Object recognition
- Distance estimation
- Dynamics estimation
- Orientation judgment
- Inspection

2) Connection/Docking

- Relative position estimation
- Relative motion estimation
- Alignment estimation

3) Transportation/Clearance

- Trajectory estimation
- Obstacle clearance judgment

Observation refers primarily to directed viewing of a specific object. Reference to or control of the manipulator is not generally required. Connection/Docking entails matching dynamics, aligning, and coupling two objects or the end effector and an object. Transportation involves the controlled movement of the manipulator arm and attached object. Obstacle clearance may be necessary.

The second dimension of classification, work volume, modifies the specific character of the various operator functions. While the extent of the work envelope runs along a continuum, a natural division of work volume into two categories appears feasible since a number of aspects of the manipulator environment vary strongly with task dimensions. Such factors as controller/end effector gain, control type, background detail and foreshortening are highly dependent on work volume.

The extremes of the manipulator work volumes are characterized as follows:

1) Small Work Volume - Typically fine control work with low control/effector gain, high scene magnification, extensive object detail but limited background detail.

2) Large Work Volume - Typically gross rate limited control, high control/effector gain, wide angle view with extensive background detail.

Examples of task classification are listed in the function-by-volume combinations of Table III-1.

TABLE III-1. TASK CLASSIFICATION

FUNCTION	VOLUME	
	SMALL	LARGE
Observation	Inspection of object surface.	Determination of position and dynamics of isolated object.
Connection/ Docking	Coupling of end effector to object mating point.	Docking of large body to second body.
Transportation/ Clearance	Fine Manipulation using tool, object assembly.	Transportation of large body, possibly between obstacles.

In extraterrestrial applications, the small work volume is typically on the order of a 2-3 foot cube, while the large work volume may be as large as the order of a 30-60 foot cube. However, classification of the dimensions of the operator's tasks depends primarily on the criteria of control type, scene magnification, etc. rather than on absolute size.

IV. VISUAL FUNCTION ANALYSIS

A. Introduction

After categorization of operator tasks a visual function analysis was conducted to determine the basic perceptual operations and display/scene characteristics required to perform the various remote tasks.

Relationships between aspects of the teleoperator visual system and task performance have been a traditional subject for study. Typically, the visual system is analyzed in terms of the characteristics of: (1) the remote environment, (2) the video system specifications, and (3) the sensory limitations of the operator. The remote environment is defined by such parameters as uncontrolled illumination, color and brightness contrasts, target size and shape, etc. It exists independent of the means to view it. The video system, the most studied of the three areas, consists of the sensor, processing, and display elements. Human sensory limitations, the least defined area, concerns the manner in which the displayed data are perceived.

The following summarizes Section IV of the First Engineering Design Report.

B. Summary

The primary objective of the analysis was to identify the critical dimensions of the visual task presentations. Rather than attempting to define video system specifications directly, the emphasis was on specifying the displayed image, its relationship to the remote environment, and the information that the operator can extract from the image. Video system characteristics such as field-of-view, iris, display brightness, etc., were therefore derived from the characteristics of the displayed image required for performance of specific tasks. The primary functional relationships are among the operator tasks, visual operations, and displayed scene parameters.

A series of simulated scenes were photographed to aid in formulating relationships among these variables. The scenes consisted of various aspects of observation, connection, and transportation in a general extraterrestrial environment. Lighting, scale (camera position and zoom), number and form of scene objects, scene markings, and orientation were varied, providing a wide range of scene combinations.

In spite of the loss of dynamics and differences in resolution between video displays and still photography, many scene perception problems were apparent, particularly in depth perception, orientation and object differentiation. Such observations were used to group related visual parameters into major aspects of scene perception. The resulting elemental parameters are discussed in the following section.

V. ELEMENTAL SCENE PARAMETERS

A. Introduction

A major objective of this project was to identify the critical dimensions in the visual scenes used in controlling remote payloads and experiments. These dimensions, or scene parameters, could then be used in an experimental evaluation of video systems. The emphasis in this effort was to identify a limited set of elemental display dimensions, so that a particular scene could be considered to occur within a unique region of a multiparameter space.

The following paragraphs contain the highlights of Section V of the First Engineering Design Report.

B. Summary

The scene parameter criteria were formulated to provide the following characteristics:

1) Parameters should be natural constructs each combining several related visual characteristics into a single element.

2) Scene parameters should be separate from the video specification parameters.

3) Each shall be amenable to subjective judgment along a continuous, quantitative scale,

4) Observer judgments should result in consistent scaling.

5) The video specification parameters, in combination with the scene parameters should be capable of defining a visual scene in terms of major dimensions affecting visual performance.

Derivation of a set of candidate elemental scene parameters resulted from an extensive literature search, discussions with visual perception experts, and analysis of the prototype visual scenes. Paring of the originally large set to a reasonable number for analysis was then accomplished according to the stated criteria. The resulting parameters are termed object differentiation, depth precision, reference and dynamics. Table V-1 includes the descriptions of the extremes of the ranges for the four parameters.

TABLE V-1. RANGE OF VARIATION OF ELEMENTAL SCENE PARAMETERS

ELEMENTAL SCENE PARANETER	RANGE OF VARIATION	
	LOW VALUE	HIGH VALUE
Depth Precision	Unfamiliar solitary object aginst distant background. No depth cues.	Object of known size in familiar surround, shadowing, and interposition.
Object Differentiation	Cluttered scene of highly similar objects and background. Limited outlining.	Two well defined, separated, dissimilar objects on unambiguous background.
Reference	Isolated object with inconsistent operator/scene coordinates no reference aids.	Operator/scene orientation correspondence. Preference plane in background,artificial horizon aid.
Dynamics	Rapid motion of object across indepently moving background.	Stationary object, background.

- Object Differentiation was a clear, early choice as a primary scene dimension. This has been extensively studied in the context of reconnaisance and character recognition both in the form of object-object discrimination and object-background discrimination. Object discrimination is difficult to measure physically as it depends on differences in brightness, color, texture, size, shape, orientation, angularlity or movement. However, it is readily scaled subjectively and strongly related to recognition performance.

- Depth Precision is the strength and fidelity of the scene depth dimensions. Relying on numerous interacting cues such as perspective, movement parallax, interposition, etc., depth precision is extremely difficult to predict objectively, but is consistently perceived as a single sensation. Also, depth precision was selected rather than perspective value to differentiate between the simple sensation and the actual fidelity of depth information, a difference particularly seen in stereo versus dual 90° monoscopic viewing comparisons.

- Reference was seen as a general concept concerning the ease of perceiving scene orientation. Scene verticality, reference objects and aids, and operator familiarity are presumed to affect the reference value. Orientation or reference is a frequently mentioned factor in remotely manned systems and again is difficult to physically quantify.

- Dynamics is a scene factor affecting both visual acuity and presentation time. Movement of object or background has primarily been studied in the context of CRT reconnaissance work, but it is important in virtually all phases of manipulation. While motion is the most easily specified of the various factors considered, it is perhaps the most difficult to simulate with simplified apparatus in a gravity environment.

VI. SIMULATION DESIGN

A. Introduction

The objective of the experimental simulation was to reproduce the essential elements of the identified remote manipulator functions. The simulation apparatus was designed to permit full operation of the alternative video systems, to facilitate full variation of the elemental scene parameters, and to incorporate the specified operator tasks. The simulation environment was intended to reproduce the essential aspects of the operator's visual requirements and constraints, rather than reproduce the full details of actual remote tasks. This simulation environment is characterized by:

1) The tasks that the operator must perform.

2) The dimensions that describe the appearance of the task.

3) The television system by which the task is viewed.

The following paragraphs contain a summary of the simulation design. For a more complete description refer to Section III of the Second Engineering Design Report.

B. Operator Tasks

Four tasks were selected based on the analysis of operator functions. The end effector coupling task, illustrated in the photograph of Figure VI-1, is primarily a dynamic positioning and alignment operation. Starting with the scene as shown in the upper view of the monitor, the operator uses four control switches to move the small solid cylinder into the cylindrical opening. In the correct final position the manipulator shaft is aligned with the longitudinal axis of the cylindrical socket.

The cylinder docking task is illustrated in the monitor photographs of Figure VI-2. The cylinder on the right is attached to the moving arm, as shown in the upper view, and is then moved into coaxial alignment with the stationary cylinder as shown in the lower view.

The third task, termed precise positioning, is illustrated in Figure VI-3. The operator is required to move the cube from the initial position shown in the top monitor view, to the final position shown in the lower view. The final position on the lower surface is marked by the dark square.

The fourth task, clearance-transportation, requires the operator to relocate the rectangular box clearing the upper curved surface, shown in Figure VI-4, and placing it as shown in the lower view. The clearance distance for this task is about 3 percent of the vertical dimension of the box.

C. Scene Parameters

The four tasks are modified by the scene parameters which were selected on the basis of the visual function analysis. For purposes of experimental manipulation, the scene parameters were set at two extreme levels. The parameters, tasks and TV systems are listed in Table VI-1, together with the range of each of these variables. The fast dynamics was operated at 3 inches per second for translation and 15 degrees per second for rotation.

A resolution parameter was added to evaluate the impact of this important variable on performance. High resolution was normally 360 TV lines per picture height and low resolution 225 TV lines per picture height.

TABLE VI-1. EXPERIMENTAL VARIABLES

VARIABLE	TYPE	DESIGNATION
TV System	Monochrome	0
	Color	1
	Stereo	2
	2 Views, Monochrome	3
Tasks	Cylinder Docking	0
	End Effector Coupling	1
	Precise Positioning	2
	Clearance/Transportation	3
Parameters	Resolution - Low	0
	High	1
	Dynamics - Fast	0
	Slow	1
	Depth Precision	
	- Low	0
	- High	1
	Object Differentiation	
	- Low	0
	High	1
	Reference - Low	0
	High	1

D. Television Systems

The major objective of the experimental investigation was to provide an evaluation of several alternative video systems in terms of the task performance obtained with the systems. The video systems were selected to represent generic classes of systems, rather than specific manufacturer's equipment. These clases included monochrome, color, steroscopic, and 2-view monochrome television systems. The low resolution parameter was further intended to simulate the performance achievable with present day solid state sensors.

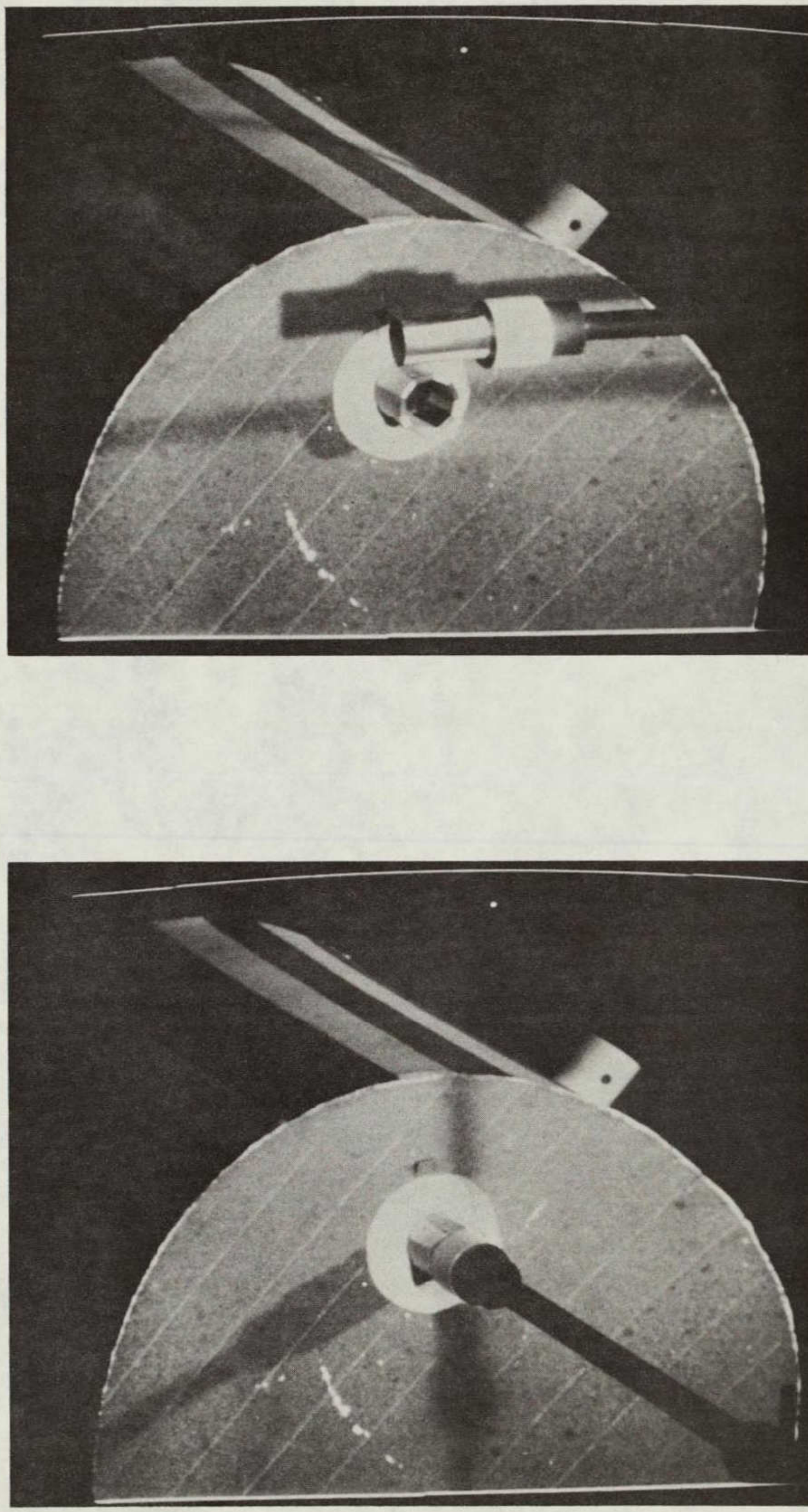


Figure VI-1. Monitor Views of End Effector Coupling Task

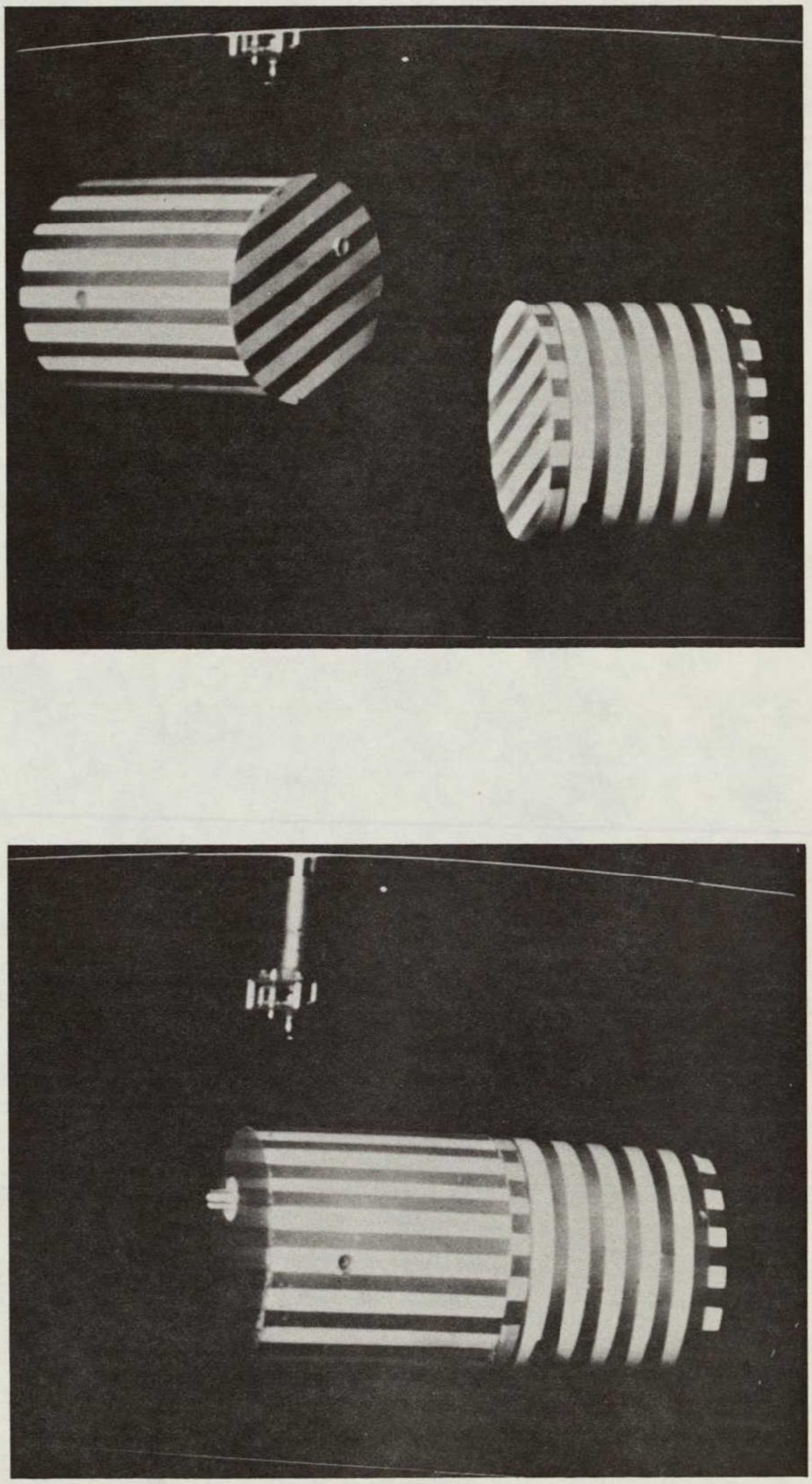
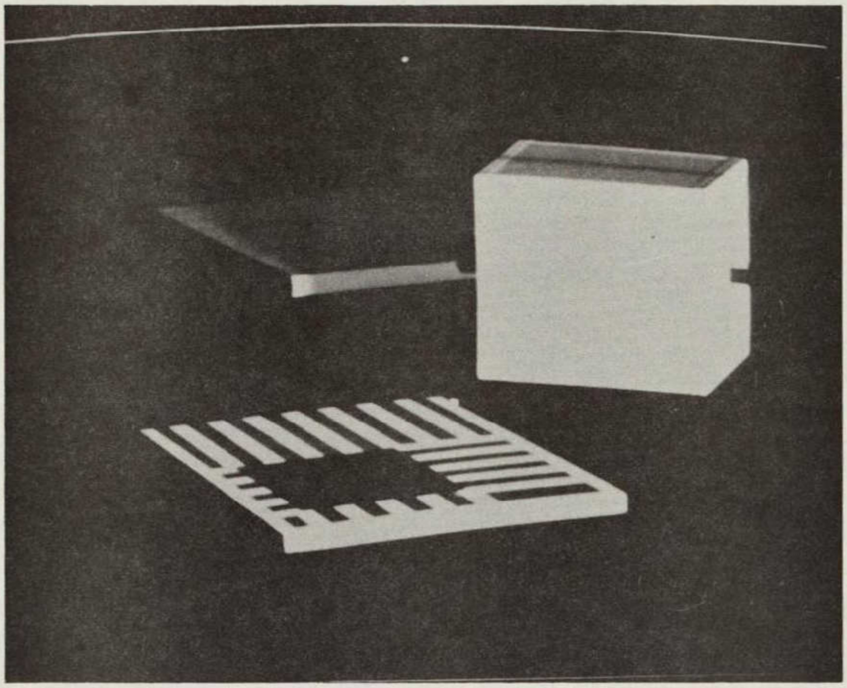


Figure VI-2. Monitor Views of Docking Task



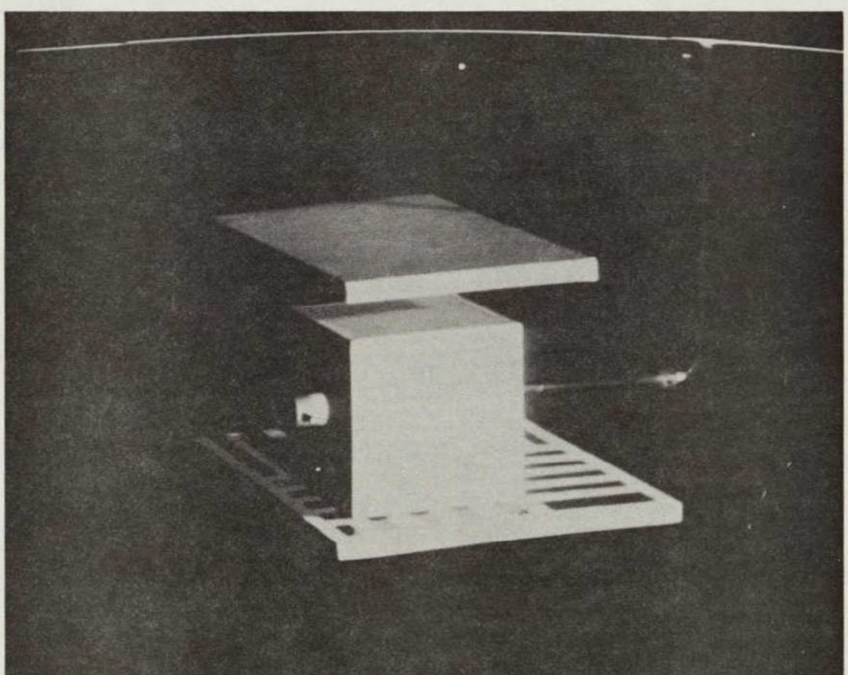
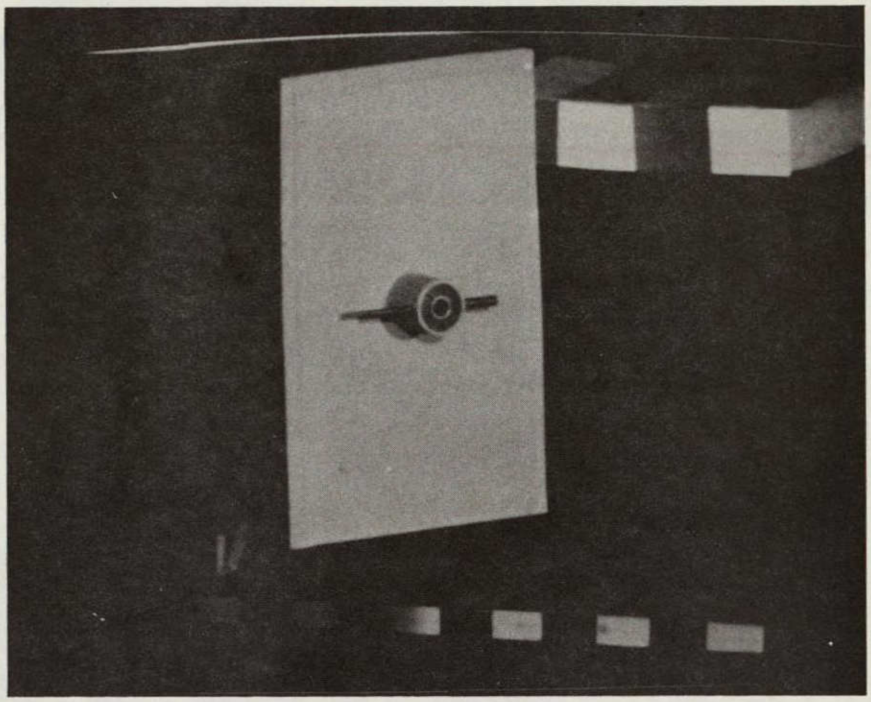


Figure VI-3. Monitor Views of Precise Positioning Task



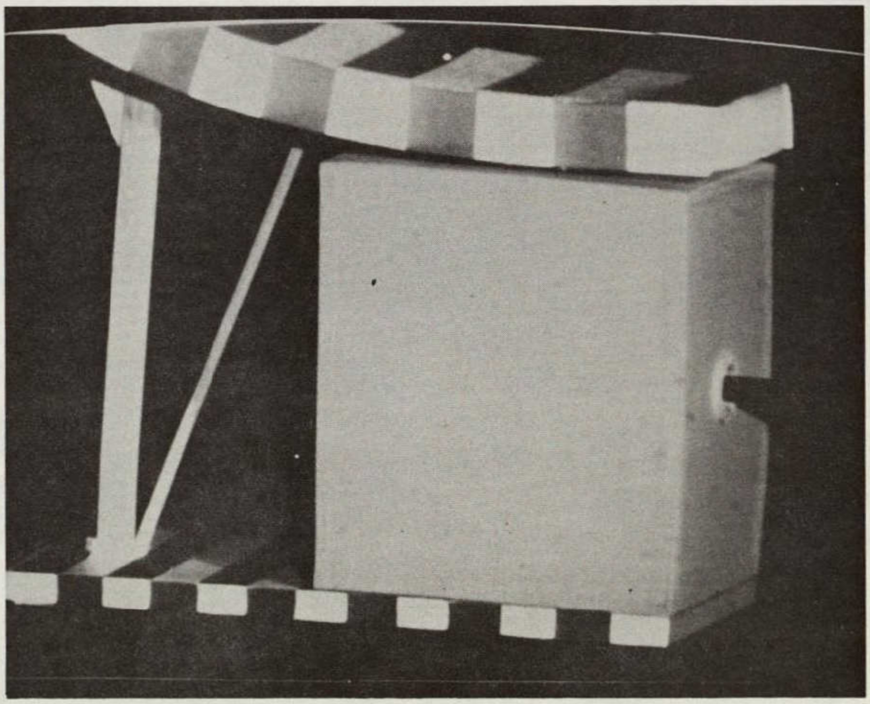


Figure VI-4. Monitor Views of Clearance-Transportation Task

VII. SIMULATION APPARATUS AND EQUIPMENT

A. Simulation Apparatus

The concept of a mechanism with a single, controlled moving element to demonstrate visual performance was discussed in the First Engineering Report (Section VII). The mechanism approach employing a traveling frame was implemented and after some debugging and minor modification has operated dependably over many hours of testing. The characteristics of the apparatus are described in the Second Engineering Design Report (Section IV) and documented in the Detailed Design Package accompanying this Final Report.

B. Equipment Arrangement

The equipment was arranged in an area reserved for this activity. The set-up is shown in Figure VII-1. The test items were located under the simulation apparatus at the approximate center of the apparatus. The fixed pieces were placed on a table covered with black cloth at a height of about 30 inches from the floor.

The main camera view was taken at an angle of from 0 to ±15 degrees to the Y axis. The viewing distance varied from 7-to-20 feet depending on the task. The second camera for the two view system was located at either 75 or 90 degrees, clockwise, from the main camera.

A black curtain was used to partition the operator from the test set-up. The entrance area was also partitioned to prevent observation of the scene. The operator saw only the TV picture of the scene after activating an elapsed time clock. Eye distance to the monitor was maintained at about 30 inches, with elevation of the monitor adjusted depending on the seated height of the operator.

The control panel was arranged to allow switch operation with both hands. Any number of switches could be activated concurrently, and the operator frequently moved the test piece in two or three directions at a time. Switch activation direction was arranged to correspond, approximately, with the actual motion as viewed by the operator, to maintain "naturalness" of the action.

C. Simulation Equipment

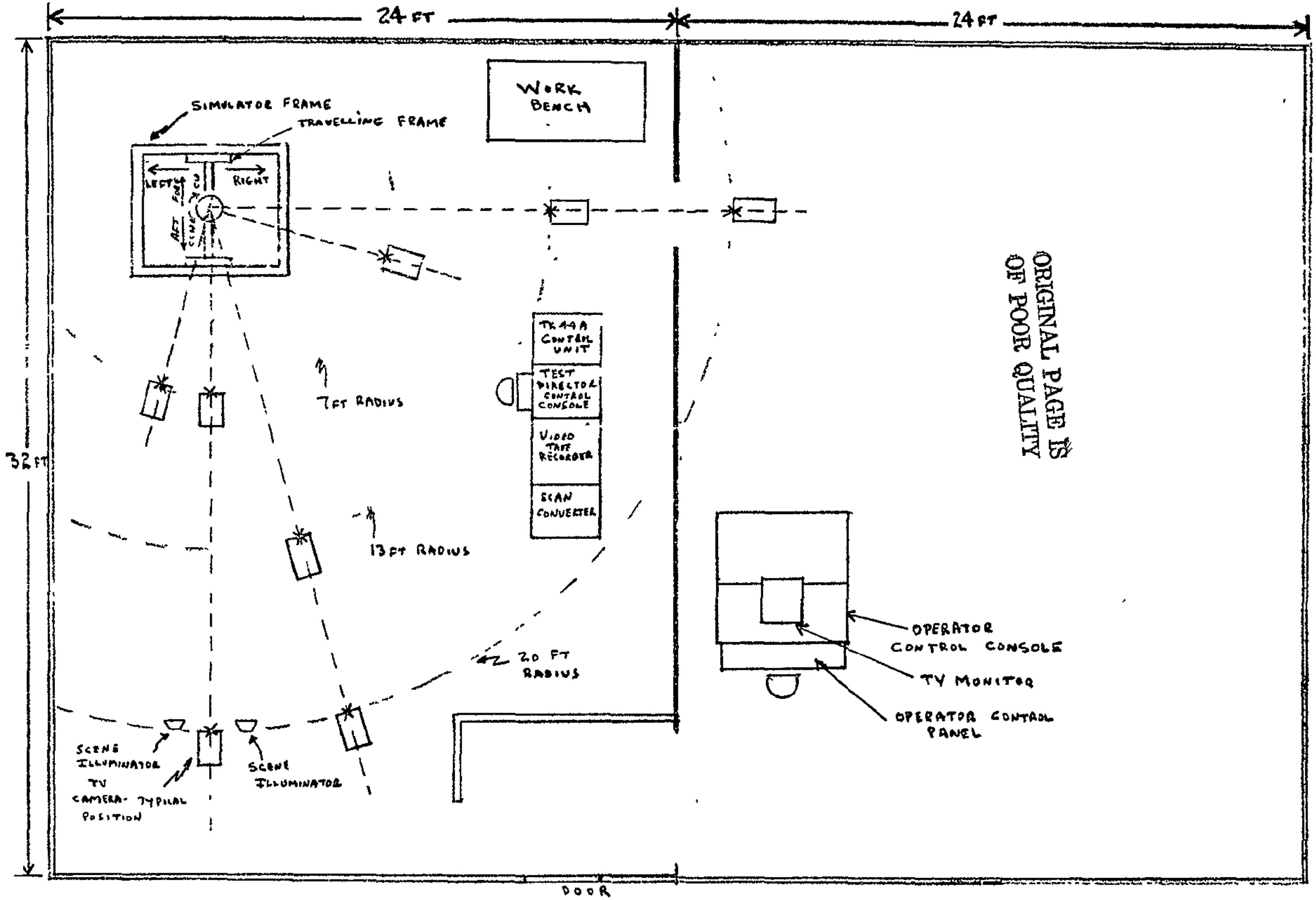
Efficient interconnection and equipment location was an essential element for smooth conduct of performance testing. In addition to the need for camera and lighting relocation, itself a time consuming element of the test phase, it was necessary to set up different electrical arrangements to permit the proper operator display and camera adjustment. Details of the equipment interconnection as well as equipment descriptions was presented in the Second Engineering Design Report (Section V).

The deliverable breadboard equipment is described and documented in the Detailed Design Package. Drawings of the deliverable equipment together with interconnection diagrams and rack layout are included in this package.

D. Stereo System Selection

Preliminary to the main simulation tasks, a screening of various potential stereo systems was performed. While each of the systems investigated offered potentially attractive features, an anaglyph system was selected for use on the simulation trials. This system provided normalization of monitor size among the trial systems and fewest performance compromises.

The selected system, described in the Second Engineering Design Report (Section V) together with the selection rationale, employed a single color monitor and two cameras providing a left and right "eye view of the scene. The left camera video was fed to the blue gun of the color monitor and the right camera video to the red gun. Suitable color filters mounted in a viewing hood were employed to separate the two pictures viewed by the operator.



SCALE: 3/16 IN = 1 FT.

Figure VII-1. Simulation Test Work Area

VIII. EXPERIMENTAL DESIGN

A. Introduction

Four basic tasks and four scene paramters were identified for experimental investigaion. In addition, four TV systems were to be compared, each at two resolution levels. A full factorial design for each variable would require data collection at 512 points. This would be particularly unweildy with 15-to-30 minutes required for each set-up and each data point replicated three times.

As an alternative to a full factorial experimental plan, a fractional factorial provided an initial examination of the entire range of the many experimental variables. The results of this first experiment then provided suggested points of specific interest and concern which were examined using a smaller multiple-replicate full factorial design.

The experimental design is discussed in the following paragraphs. For additional details, refer to Section VI of the Second Engineering Design Report.

B. Experiment I

The first test series was conducted according to the sequence requirements of a 1/4 replicate fractional factorial design. The present fractional factorial was based on a 4×2^7 factorial design with all variables examined at two levels except the TV system variable which included four levels. These four TV systems necessitated a modification of a basic 2^n fractional factorial design. Cochran and Cox (1956, p.273) describe a straightforward method of transforming a 4×2^n design into a 2^{n+2} design by using two dummy factors at two levels for the single factor at four levels.

The four operator tasks have previously been defined in terms of two conceptual dimensions, Element Relationships and Work Volume. However, for purposes of discussion the tasks may also be considered as a four-level variable in a manner similar to the TV systems. The 2^9 design for the experimental variables is shown in Table VIII-1.

TABLE VIII-1. EXPERIMENTAL VARIABLES

FACTOR LABEL	FACTOR IDENTIFICATION
A	Resolution
B	Dynamics
	TV Systems
C	Dummy Variable I
D	Dummy Variable II
E	Depth Precision
F	Object Differentiation
G	Reference
	Tasks
H	Element Relationships
J	Work Volume

1. Subjects

Eight subjects were selected from among RCA personnel to represent a range of technical training from technical school graduate to a master's level electrical engineer. These subjects had a variety of experience and expertise with television systems and video display optimization ranging from TV oriented job specialties to little or no contact. All subjects were screened for visual capabilities using the Keystone View Company Telebinocular, with the tests administered by the AED registered nurse. The subjects were selected from a pool, 18 having normal vision from a total of 47 that were tested.

2. Performance Measures

Positioning errors for the four axes of motion, performance time, number of contacts with the fixed objects, and duration of contacts were recorded for each repetition trial at each variable combination. These data were converted to means for each combination with each mean calculated over all three repetition trials, and only over the last two repetitions. The two repetition mean data are listed in Appendix A.

3. Statistical Analyses

The analysis of Variance (ANOVA) of the fractional factorial was calculated according to an adaptation of Yates' automatic method, described by Cochran and Cox (1956, p. 268-270). The interpretation of the differences among the four levels of the TV Systems is not straightforward since the four levels are represented in the two level design in the form of dummy variables. As a clarification of the performance effects of the four TV systems and the four operator tasks, analyses were performed for all pair-wise comparisons among the TV systems and among the tasks, using the Duncan Multiple Range Test (Kirk, 1968, p.93).

C. Experiment II

Based on the initial analysis of the performance in the first experiment, the second test series was designed to further examine the effects of all four TV systems within the context of more extensive variation in Object Differentiation. It was suggested that this latter parameter most closely refers to object markings and other scene characteristics which are modified by adding enhanced scene details. Thus, a more refined experiment was expected to provide relevant data for selecting scene markings.

1. Subjects

The three subjects who demonstrated the best overall performance in the first experiment (subjects 1, 2, and 6) were selected for the second test series. This procedure was adopted under the assumption that the test results would logically be extrapolated to a population of highly trained and experienced operators. Therefore, the subjects should more closely resemble the population of experienced operators.

2. Experimental Design and Analyses

The second test series was conducted as a full 4 x 3 x 2 factorial with three replications. Each subject encountered all treatment combinations of 4 TV systems (monochrome, color, stereo, and 2-view), 3 levels of Object Differentiation (high, medium, and low), and 2 tasks (Docking and Precise Positioning). The 3 repetition and 2 repetition means for four dependent variables (RMS error, scaled RMS error, contact-seconds, and performance time) were analyzed with a factorial Analysis of Variance statistical program (Dixon, 1968, p. 495-510).

IX. TEST RESULTS

A. Test Series I

The contributions of the independent variables to the three performance measures are summarized in Figures IX-1, 2, and 3.* These figures show the mean contributions of the manipulated variables on accuracy (positioning error), performance time, and errors (contact-seconds), and illustrate the grand mean effect of each task, calculated for the means across the last two repetitions at each variable combination. The 2-repetition means were used under the assumption that the initial trial for each combination was a practice trial which may have been heavily influenced by transitory effects.

A series of analyses of variance (ANOVA) were conducted on the data, to establish the reliability of the effects illustrated in these figures. Those performance differences among the major variables which are statistically reliable are illustrated in the figures as vertical dashed lines. Any distance between two points on the adjacent line which exceeds the dashed line represents a statistically significant difference ($\rho < .05$) between those points. That is, the probability, ρ, of the difference being due to chance alone is less than 5 percent. For example, as shown in Figure IX-1, the operators were able to position the objects significantly more accurately using a 2-View TV system than with any of the other systems. Similarly, significantly less positioning error occurred with the Coupling task than with the Docking or Clearance task; however, the positioning error for the Precise Positioning task was not reliability different than the other tasks.

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*These data were presented in the Second Engineering Design Report (for both the first and second test series) but errors in data entries for the first test series computer inputs are corrected here. Previously supplied second test series data are believed to be accurate.

The rms positioning error entries for Figure IX-1 and for all figures and tables in this section (and Appendix B) have been scaled to account for differences in field-of-view for the four tasks. Scaling values are 1.0, 0.317, 0.488, and 0.8 for coupling, docking, positioning, and clearance, respectively. (See Table IX-5 for scene widths).

The complete summary of the analyses of variance is shown in Tables IX-1 and IX-2. Table IX-1 includes the degrees of freedom and mean square terms, including the error mean square which was used in the subsequent pairwise comparisons among the four tasks and four TV systems. Table IX-2 presents the means for all main effects and first order interactions.

The treatment mean represents the difference between the two levels, with the grand mean centered between all two-level factors. The statistical significance of the two-level treatment effects and the simple interactions are given directly in Table IX-2. Although several first-order interactions are significant effects, the majority are not. Thus, the illustration of the main effects in Figures IX-1 through IX-3 demonstrate the major differences among the scene parameters, tasks, and TV systems.

Interpretation of the four levels of TV Systems and Tasks is complicated by the use of dummy variables in the two-level factorial design. Therefore, a Duncan Multiple Range test of pairwise comparisons was conducted between all pairs of TV systems and all pairs of tasks to establish significance.

To provide a single index of performance, the three dependent variables were combined for each data point according to the following equation for Combined Relative Performance (CRP):

TABLE IX-1. ANOVA SUMMARIES FOR 2-REPETITION TRIAL MEANS

SOURCE	d.f.	MEAN SQUARES			
		ACCURACY (POSITION ERROR)	PERFORMANCE TIME	ERRORS (CONTACT-SECONDS)	COMBINED RELATIVE PERFORMANCE
Blocks (Subjects)	8	.023	7106	3561	1.16
Main Effects	9	.080**	16292**	4653	2.25**
2-Factor Interactions	48	.026	5283	3130	.89
Error (from remaining interactions)	62	.017	3931	3187	.93

Experiment I

*p<.05
**p<.01

TABLE IX-2. TREATMENT MEANS FOR 2-REPETITION DATA

TREATMENT LABEL	TREATMENT IDENTIFICATION	POSITIONING ERROR	PERFORMANCE TIME	CONTACT ERROR	COMBINED RELATIVE PERFORMANCE
	GRAND MEAN	165	157.6	22.7	1 000
A	RESOLUTION (RE)	- 023	2 5	9.8	099
B	DYNAMICS (DY)	004	46 7 **	-7.8	- 014
	TV SYSTEMS				
C	DUMMY 1 (TV-A)	- 066 **	-20.7	-11 3	-.339 *
D	DUMMY 2 (TV-B)	-.048 *	25.5 *	5 8	.039
CD	DUMMY 3 (TV-C)	- 041	-1.3	-12 2	.271
E	DEPTH PRECISION (DP)	-.069 **	-8.5	-8 0	-.280
F	OBJECT DIFFERENTIATION (OD)	- 076 **	16 7	-13 6	-.322
G	REFERENCE (RF)	.017	-10.5	-6 0	-.072
	TASKS				
H	ELEMENT REL (ER)	.022	-16.1	-0.7	-.005
J	WORK VOLUME (WV)	062 **	24 5 *	26.5 **	563 **
HJ	ER x WV	-.041	35 3 **	4.3	059
	2-FACTOR INTERACTIONS				
AB	RE x DY	.028	10.8	-7 8	-.032
AC	RE x TV-A	-.022	6.6	2 4	.001
AD	RE x TV-B	047 *	-12 2	.1	.075
ACD	RE x TV-C	- 024	9 9	-5.2	-.099
AE	RE x DP	019	3 2	-7.6	-.063
AF	RE x OD	- 024	-13.6	-18 4	-.342 *
AG	RE x RF	.023	-4 3	-11.2	-.131
AH	RE x ER	-.001	17 3	5.5	120
AJ	RE x WV	-.027	13 7	16.9	228
AHJ	RE x EL x WV	-.013	-3 3	-1.7	- 062
BC	DY x TV-A	-.016	18.6	2.7	043
BD	DY x TV-B	.019	-4.4	-16 3	- 206
BCD	DY x TV-C	- 030	12.4	19 7 *	.260
BE	DY x DP	-.016	17.3	12.2	.189
BF	DY x OD	-.036	-11 4	5.2	- 016
BG	DY x RF	023	-4.3	-11 2	- 131
BH	DY x ER	001	9.9	-0 3	.023
BJ	DY x WV	- 024	-0.9	-8 9	- 178
BHJ	DY x ER x WV	-.057 *	11 5	-1 5	-.117
CE	TV-A x DP	-.004	8 9	0 9	019
DE	TV-B x DP	.012	-6 0	-3.3	-.031
CDE	TV-C x DP	039	9.3	16 3	.342 *
CF	TV-A x OD	.047 *	-13.1	4 0	121
DF	TV-B x OD	- 001	6.0	-1.7	- 011
CDF	TV-C x OD	.006	-25.1 *	8 7	092
CG	TV-A x RF	-.044	-1.1	14 4	126
DG	TV-B x RF	.018	-14 7	-18 4	- 270
CDG	TV-C x RF	-.034	-6 2	-3 1	- 132
CH	TV-A x ER	-.024	14 4	-14 7	- 239
DH	TV-B x ER	004	-8 6	12 5	178
CDH	TV-C x ER	.033	8.6	2.9	.132
CJ	TV-A x WV	006	20.4	-2.5	.131
DJ	TV-B x WV	-.031	-7 9	4 9	- 003
CDJ	TV-C x WV	- 027	-15 7	-11.9	-.261
DHJ	TV-B x ER x WV	.004	22.2 *	11.3	.217
CDHJ	TV-C x ER x WV	048 *	7.4	-0.4	.102
EF	DP x OD	.010	-8.6	7 9	.122
EG	DP x RF	-.023	4.9	-4 2	- 101
EH	DP x ER	.016	13 0	-2 2	031
EJ	DP x WV	-.069 **	10 4	-6 1	-.202
EHJ	DP x ER x WV	.036	-4 7	-4 5	-.009
FG	OD x RF	-.030	2 6	8.5	.066
FH	OD x ER	016	-20.2	-8.3	-.128
FJ	OD x WV	- 030	-10.3	-21.0 *	-.387 *
GH	RF x ER	-.017	-10.4	-15.8	-.293
GJ	RF x WV	-.019	13.1	-10 8	- 174
GHJ	RF x ER x WV	- 030	15 9	-9 9	- 237
BLOCKS	SUBJECTS	.009	-16.2	-0.2	-.024
"	"	.052 *	19 4	-10 3	- 0001
"	"	024	9.9	10.5	.229
"	"	- 022	7.0	01	-.256
"	"	- 0003	3.4	-4 4	-.054
"	"	.003	-22.8 *	-19.8 *	-.330
"	"	.011	21.4	10 6	229

* $p < .05$

** $p < .01$

$$CRP = \frac{\text{Relative Position Errors + Relative Performance Time + Relative Contact Error}}{3}$$

where

$$\text{Relative Position Error} = \frac{\text{Postiion Error}}{\text{Mean Position Error}},$$

$$\text{Relative Performance Time} = \frac{\text{Performance Time}}{\text{Mean Performance Time}}, \text{ and}$$

$$\text{Relative Contact Error} = \frac{\text{Contact Error}}{\text{Mean Contact Error}}.$$

The mean for each variable was calculated over all 128 data points in the experiment. The effect of this technique was to normalize all dependent variables around a common mean of one and to include the performance in a single index. The Combined Relative Performance was subsequently treated as a further dependent variable. The results of the analysis of variance for this variable are also shown in Tables IX-1 and IX-2.

Figure IX-4 illustrates the contributions of the independent variables to the single performance index. This figure clearly demonstrates the significant improvement gained by using a 2-View TV system for performing the tasks as compared with the black and white monoscopic system. Although improved performance was noted by using a color or stereoscopic TV system, the difference is not reliably different in the statistical sense.

B. Test Series II

The results of the analyses of variance for the second test series are illustrated in Table IX-3. Pairwise comparisons were made among the four video systems to provide a detailed analysis of these systems. The results of these comparisons

TABLE IX-3. ANOVA SUMMARIES FOR 2-REPETITION TRIAL MEANS

SOURCE	d.f.	MEAN SQUARES		
		Positioning Error	Performance Time	Contact Error
TV System (TV)	3	.0186**	934	32.0
Object Diff. (OD)	2	.0004	1038	118.4
Task (TK)	1	.0600**	3416*	1420.4*
TV x OD	6	.0008	194	285.2
TV x TK	3	.0089*	2376*	260.7
OD x TK	2	.0038	83	45.6
TV x OD x TK	6	.0015	500	437.7
Error (Within Replicates)	48	.0028	737	341.8

*$p<.05$
**$p<.01$

Experiment II

are summarized in Table IX-4, which contains also the data from the first experiment, in parentheses. These data are the mean performance values for the three subjects who performed the tasks in both experiments. While data are averaged over different experimental conditions in the two experiments they provide an indication of the range of variation across the experiments. In general, the subjects demonstrated greater accuracy while requiring less time to perform the tasks in the second experiment. This effect is not surprising since the first experiment could be considered to be an extended training and practice session in preparation for the second testing sequence.

C. Performance Assessment

The major difference noted between the first and second test series was the reduction in required mean performance time and positioning error in the second series, due to increased practice and to selection of the better operators. The surprising result of the second test series was the lack of any significant differences due to the manipulation of the Object Differentiation parameter, particularly with respect to Positioning Errors which was a significant effect in the first test series. The following comments are based on detailed examinations of the performance in the first test series. However, with the exception of the differences noted above, the comments apply to the second test series.

1. Tasks

The performance effects of the four manipulation tasks are illustrated separately in Appendix B. The 12 figures in the appendix shows the TV system, subject, and parameter contributions to scaled positioning error, performance time and contact errors for each of the four tasks of Experiment I. As noted previously the operators demonstrated significantly better performance on the Coupling and Precise Positioning

TABLE IX-4. MEAN PERFORMANCE VALUES FOR FOUR TV SYSTEMS

PERFORMANCE INDEX	VIDEO SYSTEM			
	0 B&W	1 COLOR	2 STEREO	3 2-VIEW
Accuracy (Positioning Error)	.089(.164)	.125(.191)	.093(.156)	.047(.068)
Performance Time	84.5(157.2)	92.5(139.0)	78.8(125.8)	94.3(137.3)
Errors (Contact-Seonds)	6.42(49.6)	7.07(7.8)	6.32(4.8)	9.18(7.2)

Experiment II

(Figures in parentheses indicate comparable data from Experiment I. Values underlined by a common line do not differ significantly.)

tasks than on the Docking and Clearance tasks. The former tasks are characterized not only by the better mean performance (i.e., lower mean Combined Performance scores) but also by the reduced variance among the subjects. In all cases, the subjects accounted for a dramatic portion of the variation. This highlights the importance of carefully selecting and training the operators to obtain optimum performance in remote manipulation tasks.

2. TV Systems

Substitution of color for a basic black and white video system does not appear to have a strong overall effect. In only one instance, does a color system significantly differ from the black and white system and that effect is to introduce a greater positioning error. It should be noted, however, that in order to achieve a high level of object differentiation, for all systems, with a particular test object complement, colored objects and markings were accompanied by brightness differences. Further color enhancement of the objects is certainly possible, likely leading to improved color system performance.

As shown in Figure IX-4, the introduction of a second black and white view produces a significant improvement in performance, particularly with reference to positioning accuracy. This effect is seen across all tasks where the 2-View TV system shows generally superior performance. The 2-View TV system is also ranked significantly higher, according to operator preference, than all other systems. This suggests that the operators found the task less demanding with the additional scene view.

The mean performance of the stereoscopic TV system across all tasks indicates that although improvement may be expected, the improvement is not strong enough to be statistically reliable.

However, this tends to obscure the effect of using a stereoscopic system for specific tasks. Using the CRP process described, the stereo system and 2-view system were roughly equivalent for all but the docking task on the first test series.

It is also noted that the dramatic decrease in performance for the docking task using the stereoscopic system was not demonstrated in the second test series. However, a substantial decrease in performance for the stereo system was obtained on the positioning task with the more skilled operators of the second test.

3. Scene Parameters

The scene parameters had relatively little effect on performance, particularly in the second test series which used better and more experienced operators. Resolution and Reference did not appear to reliably influence any of the performance indicies. To the extent that Reference refers to an initial orientation, extended practice may tend to overcome any disorientation or confusion of reference coordinates.

Dynamics did not have any effect on positioning accuracy or contact errors; however, it heavily influenced the performance time. This is hardly a surprising result since the parameter refers specifically to the manipulator speed of motion.

Depth Precision also produced a small but expected effect on positioning accuracy. Additional cues for depth produced significantly better accuracy and the operator's preferred to function with these additional cues.

On the basis of the results from the first test sequence, Object Differentiation was expected to postively influence positioning accuracy. Thus, it is particularly surprising to note that this parameter did not exert an influence on the operator's performance during the second test sequence even though this sequence provided a detailed examination of the parameter at three levels.

D. Miscellaneous Tests

A series of tests were conducted to obtain supplementary data supportive of system characterization. Three specific items were investigated: camera field-of-view, camera view angle (azimuth and elevation), and location (viewing position) of the second camera for a two view system.

The camera field-of-view for the four simulation tasks varied from a scene width of 10 inches for coupling to 31.5 inches for docking. For a TV system of 360 TV lines per picture height, the width of a single element in the scene is .021 inch (see Table IX-5 for dimensions for each task) for the coupling task.

TABLE IX-5. SCENE ELEMENT WIDTHS FOR SIMULATION TASKS BASED ON 360 AND 225 TV LINES PER PICTURE HEIGHT (UNITS IN INCHES)

TASK	SCENE WIDTH	ELEMENT WIDTH	
		HI RES	LO RES
Docking	31.5	.066	.105
Coupling	10.0	.021	.033
Manipulation	20.5	.043	.068
Clearance	12.5	.026	.042

This element dimension corresponds to .024 inches at the monitor for the 8.75-by-11.67 inch raster. At the 30-inch viewing distance, the limit of discernability of about one minute of arc for the obersver is .0087 inch. The operator was therefore able to "use" all the detail available in the display.

The coupling task requires that the operator place a .5 inch end effector into a .625 inch hollow cylinder. By definition then, the minimum accuracy tolerable for this task is .125 inch or about six picture elements. The trained operator is able to perform this task, virtually without error, although concentration is required.

Doubling of the normal field-of-view, i.e., increasing the width to 20 inches, makes this task extremely difficult. Even the well trained operator cannot perform this task consistently without error. On the other hand, decreasing the width to 5 inches eases the task so that only slight effort is required. It therefore appears that location accuracies of about 5 TV lines should represent the limit of task requirements for a single view system. Somewhat better accuracy appears to be reasonable with the 2 View System.

It was also noted that setting the camera to the 5-inch width before the start of the test causes a loss of perspective and creates difficulty in alignment. Changing the field-of-view from wide to narrow as the test proceeds appears to be the most efficient approach to this task as well as for the general remote operation.

The camera azimuth angle, for the three single location systems, appears to be fairly uncritical. For three of the tasks, (docking, coupling, clearance) any azimuth angle between about 10 and 45 degrees, or more, is satisfactory, although near

0 angles are to be avoided. The problem with the near zero angles relate to a loss of depth cues and causes fore/aft positioning error to increase. The fourth task which involves location on a plane surface appears to tolerate azimuth angles near zero as well, difficulty with depth depending more on elevation angles.

At elevation angles below about 10 degrees, the fore/aft location accuracy on a shelf is quite poor, and worsens as the elevation angle approaches zero. As the elevation angle increases above 10 degrees the accuracy improves, and at about 30 degrees is quite good, see Figure IX-5 for geometry. Accuracies of better than 0.1 inch were easily achieved in this direction. On the negative side, the height cues were much reduced by the increased angle and care was required to avoid hitting the upper shelf, a problem virtually non-existent at a 15-degree or smaller angle.

The viewing angle situation is drastically altered when a second view is available. For the location on the shelf task, low elevation angles are quite acceptable, the second view providing the missing fore/aft information. It is also quite acceptable for the main view to be placed at near zero azimuth angle for the other three tasks since this view no longer provides the primary depth information. In fact, zero azimuth angle appears to be preferable for the cylinder docking task where axial, angular misalignment is the largest source of error.

With the exception of the cylinder docking type task, the angular location of the second camera does not appear to be important. The end effector coupling task was run with second view angles from 5-to-90 degrees without significant performance difference being noted. The cylinder docking performance appears to improve as the second view approaches close to alignment with the edge of the stationary cylinders. However, exact alignment with the forward edge of the cylinder appears to result in obscuration of the desired information and is somewhat poorer than a slight offset, say about 5 degrees, see Figure IX-6.

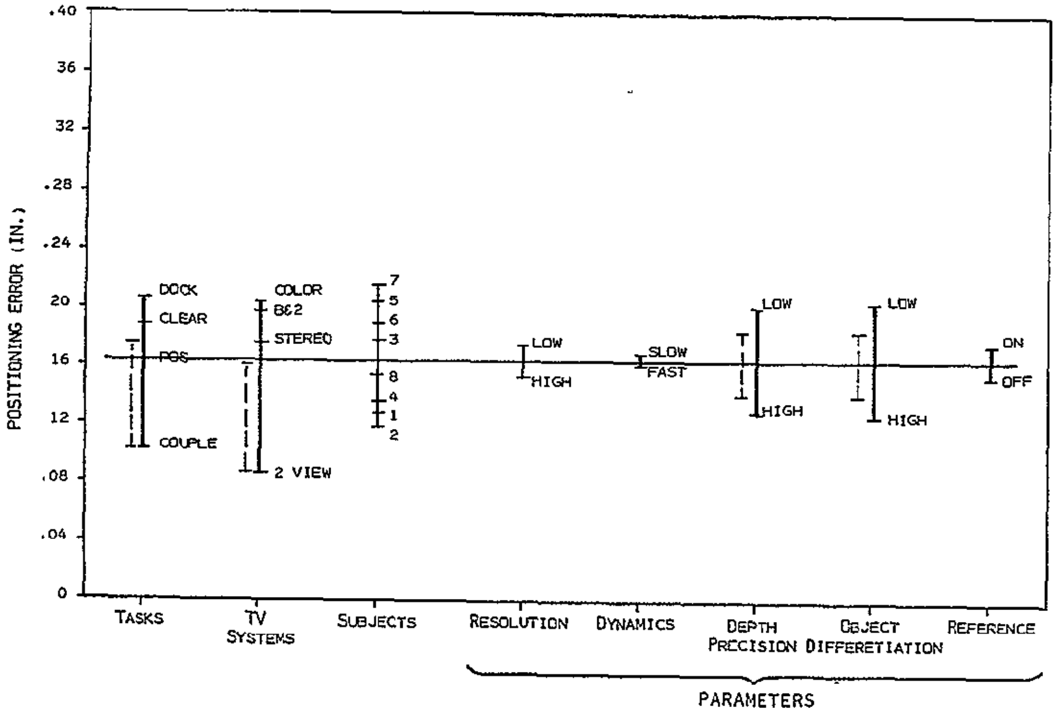

Figure IX-1. Contributions of Independent Variables to Positioning Errors

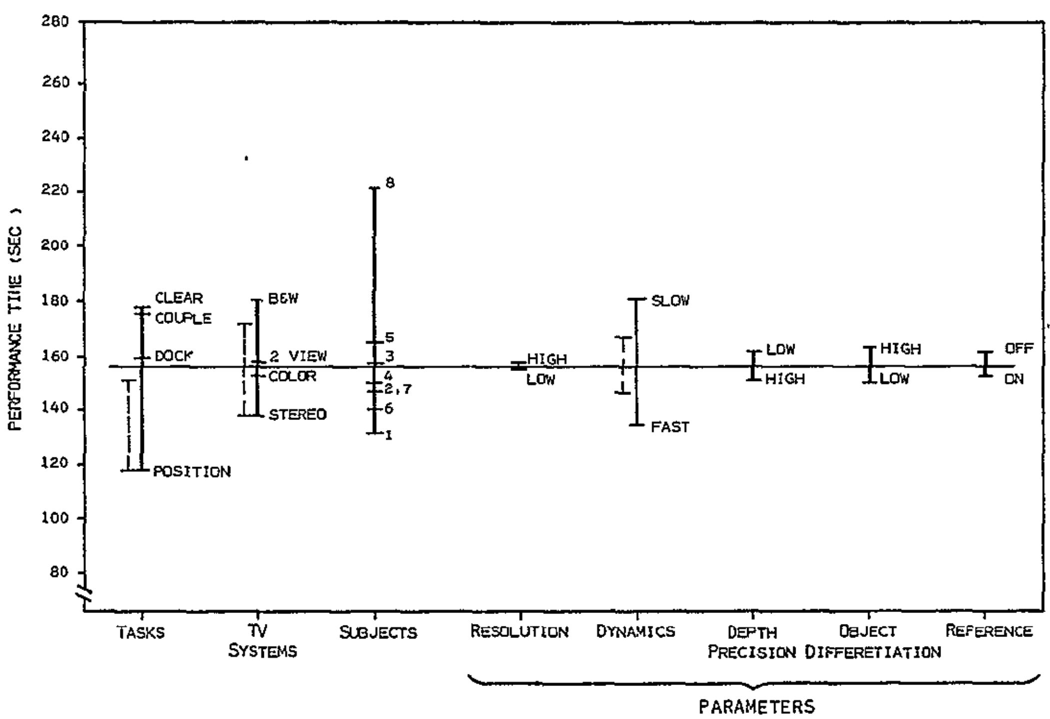

Figure IX-2. Contributions of Independent Variables to Performance Time

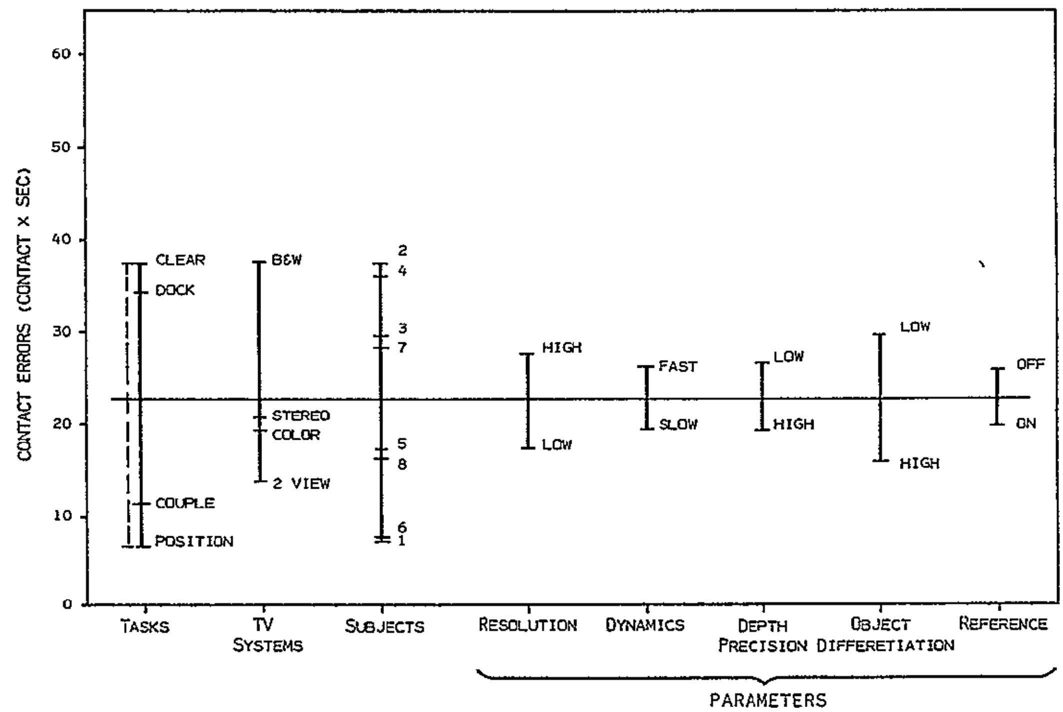

Figure IX-3. Contributions of Independent Variables to Contact Errors

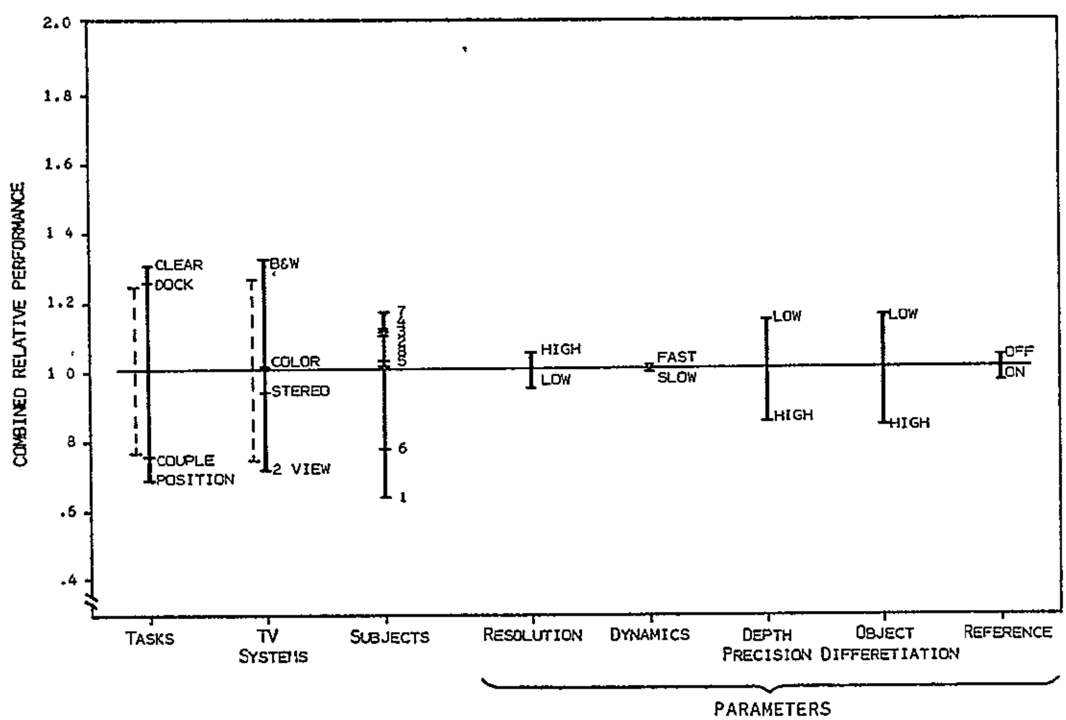

Figure IX-4. Contributions of Independent Variables to Combined Relative Performance

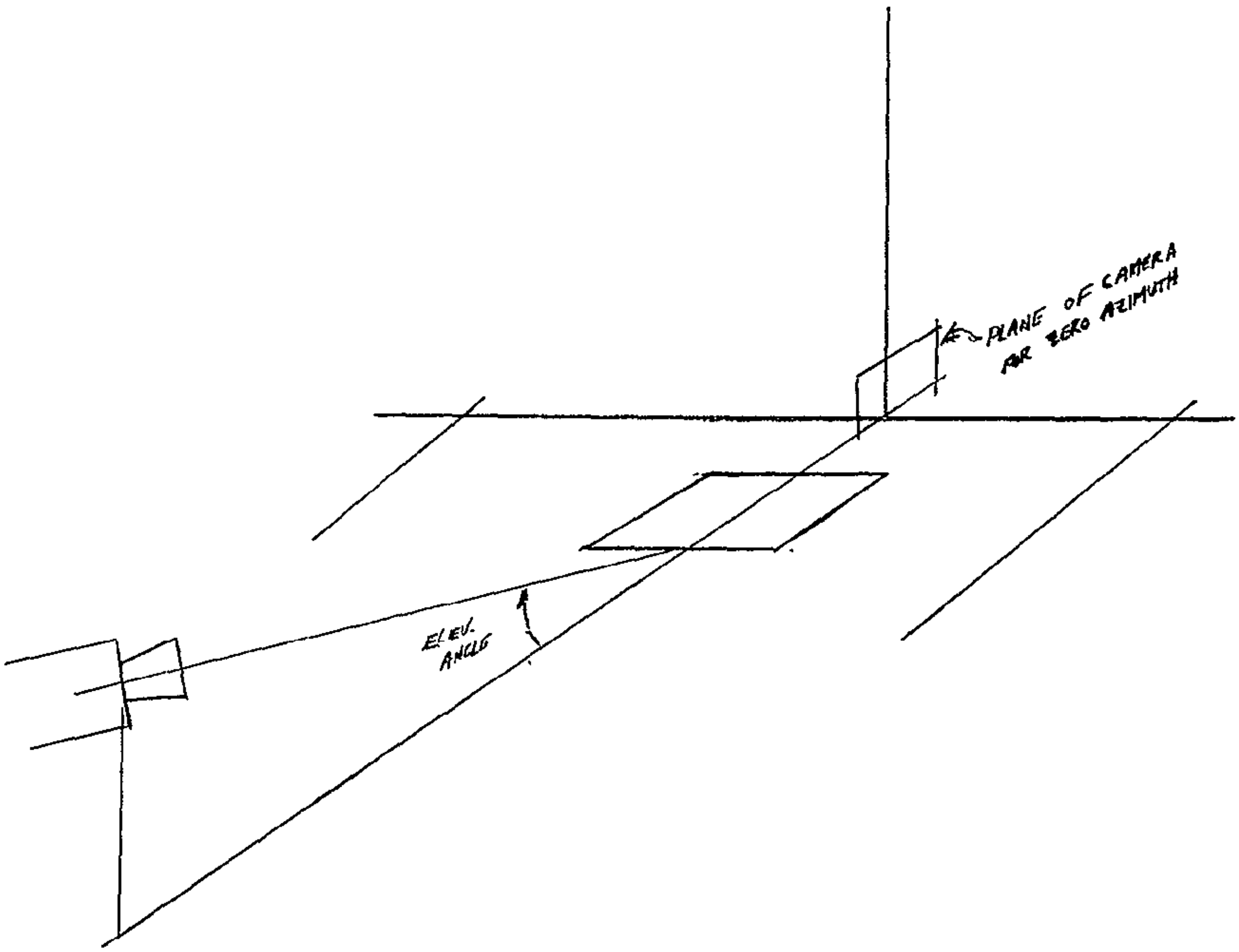

Figure IX-5. Elevation Angle Geometry for Location on Plane Surface

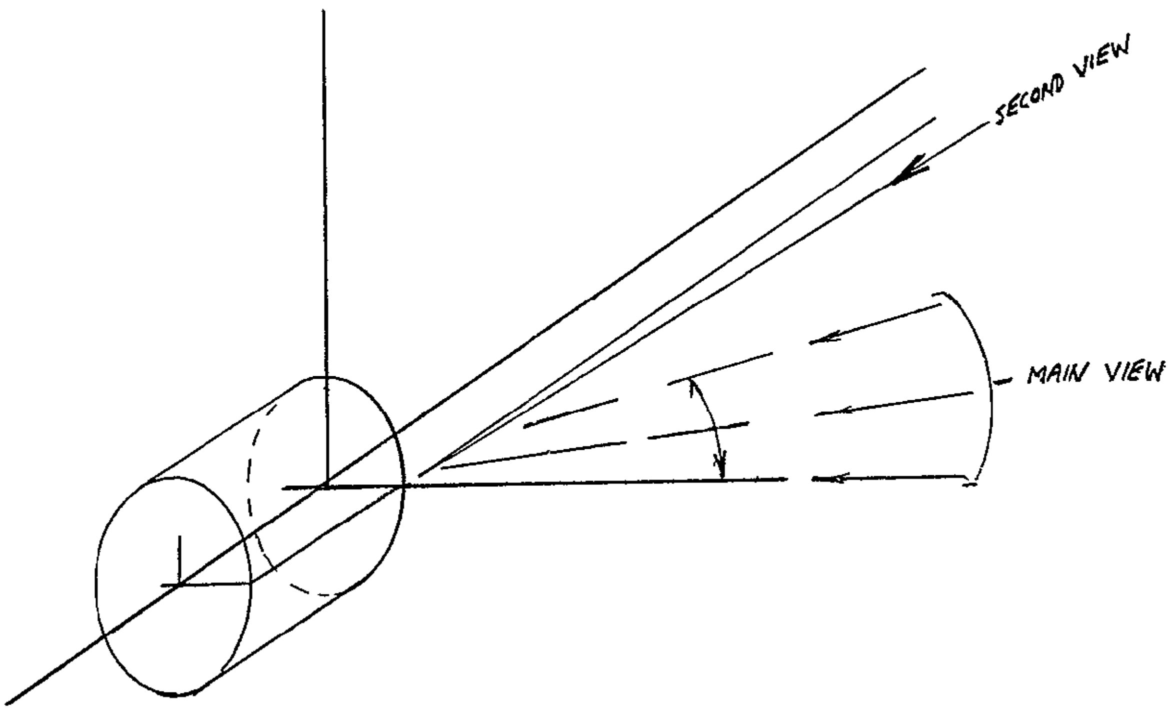

Figure IX-6. Camera Locations for 2 Views of Cylinder

X. SYSTEM RANKINGS

A. System Effectivity

The performance of the various TV systems on the experimental tasks, discussed in the previous section, were scaled by a somewhat different process than used in the previous assessment to obtain equal weight for each task. Rather than employing the mean value of the particular performance measure across all tasks, the mean value for each task, on each of the three performance measures, was used. Thus the time rank for the 0 system, on Task 1 $\left(R_{0T1}\right)$ is given by:

$$R_{0T1} = \frac{P_{T0}}{1/4\left[P_{T0} + P_{T1} + P_{T2} + P_{T3}\right]} \Bigg| \text{TASK 1}$$

where P_{T0} is the mean value of the performance measure time for system 0 (see Table VI-1 for system designations) across all operators of the test series. This results in a mean effectivity of unity for each measure, across the four systems.

The dimensionless effectivity ranks for the first test series are listed in Tables X-1, 2, and 3, for the performance measures accuracy (A), time (T), and errors (E) respectively. The data is based on the last two repetitions of each trial. The overall, mean, effectivity across the four tasks, listed in the last column of the tables, is obtained by averaging the task values.

When ranked in this fashion, the TV system having the lowest value is indicative of highest performance. Thus on the coupling task, Table X-2, the effectivity of 0.54 for the stereo system and 1.08 for the color system indicates that the mean time for all of the operators using the stereo system in the first trail series, on this task, was one-half of the mean time for all of the operators using the color system.

TABLE X-1. SCALED ACCURACY (RMS POSITIONING ERROR) BY TASK - FIRST TEST SERIES

SYSTEM	TASK				
	DOCKING	COUPLING	POSITIONING	CLEARANCE	MEAN
Monochrome	1.25	1.13	1.34	1.00	1.18
Color	.94	1.30	1.26	1.44	1.30
Stereo	1.48	.87	.84	.94	1.03
2 Views	.33	.70	.57	.62	.58

TABLE X-2. SCALED TIME PERFORMANCE BY TASK - FIRST TEST SERIES

SYSTEM	TASK				
	DOCKING	COUPLING	POSITIONING	CLEARANCE	MEAN
Monochrome	1.09	1.38	.96	1.11	1.14
Color	.86	1.08	1.07	.93	.99
Stereo	1.12	.54	.91	.89	.87
2 Views	.93	1.00	1.06	1.06	1.01

TABLE X-3. SCALED ERROR (CONTACT-SECONDS) PERFORMANCE BY TASK - FIRST TEST SERIES

SYSTEM	TASK				
	DOCKING	COUPLING	POSITIONING	CLEARANCE	MEAN
Monochrome	.99	1.73	1.18	2.39	1.55
Color	.50	1.45	1.35	.90	1.05
Stereo	1.89	.57	.37	.19	.75
2 Views	.72	.26	1.11	.53	.65

The scaled performance on individual measures was combined to obtain a single effectivity scale. Each measures was given equal weight for this combination process. Then the overall monochrome rank is given by,

$$R_{\overline{0}} = \frac{R_{0A} + R_{0T} + R_{0E}}{3},$$

the mean of the three scaled measures, across the four tasks of the first test series. The results of both the first and second test series are given in Table X-4 which also contains the final performance ranking averaged across the two test series.

TABLE X-4. OVERALL SYSTEM EFFECTIVITIES

SYSTEM	FIRST SERIES	SECOND SERIES	MEAN
Monochrome	1.29	1.19	1.24
Color	1.09	1.09	1.09
Stereo	.88	.88	.88
2 Views	.74	.84	.79

The data was treated in a variety of ways before settling on the described process. Varying weight, usually with more emphasis on accuracy (positioning error), was attempted as was some weight for the operators subjective judgement. Neither of these changed the relative rankings, and for the attempted weighting had little effect on the scales. The same is generally true if the individual measures are combined across the tasks, rather than across the test series. In the absence of a particular mission profile having task definition, and task importance to the mission success, the described process and the presented tabulations appear to provide a solid basis for establishing system effectivity.

It should be noted in evaluating the date that the entries across trial series show substantial fluctuation. It appears that the accuracy results are somewhat more consistent than the other two measures. Errors, contact-seconds, in particular show quite wide variations. Two factors are thought to be significant: training of the operators and differences among operators. The second trial series used the three best operators from the first series and, of course, had more extensive training.

No attempt was made for these tabulations to differentiate among data entries having statistical significance according to the analysis described earlier. It was thought best to maintain all measured values to permit identification of trends, while recognizing that small differences are unlikely to be important.

B. System Block Diagram

In order to perform a burden analysis which identifies measurable characteristics of equipment other than the performance measures described above, it is necessary to establish baseline equipment complements for each system. These complements were obtained by generating the functional block diagram shown in Figures X-1 through 4.

The monochrome system, Figure X-1, is the simplest of the four. The elements consist of a single camera with zoom lens mounted on a pan/tilt unit and remotely controllable from the operator's location, a monitor, and control and processing units. The block labeled control encompasses the functions of sync generation, command encoding and generation, and signal routing. The video processor provides the functions of line equalization, processing, and signal distribution.

The color system, Figure X-2, is assumed to be of the field sequential type with the camera employing a field-sequential lens assembly with integral color wheel and filters. Required in addition are a scan converter for providing flicker free color and a color monitor replacing the black and white unit of the monochrome system. Other elements of the system are unchanged.

The stereo system, Figure X-3, employs two monochrome cameras mounted on the pan/tilt unit via an adapter component which includes a pointing (convergence) angle adjustment mechanism. The lens controls are assumed to be ganged so that field-of-view will track to maintain sizing match of the two video outputs. The monitor is assumed to provide a two-color (anaglyph) display incorporating a viewing hood with color separation filters.

For two views, two monochrome cameras are used each on individual pan/tilt units (Figure X-4). A second monochrome monitor and additional encoding and processing circuitry is assumed, as compared to the single camera monochrome system. Lens controls are independent in contrast to the stereo system.

C. Burden Analysis

Equipment burdens as used here include those factors or attributes of the equipment that do not directly contribute to the usual, measurable performance characteristics. These burdens have been lumped into six categories:

1) Cost
2) Weight
3) Volume
4) Power
5) Maintainability
6) Reliability

The first four factors are used in the usual sense. Maintainability is intended to include ease of set-up and maintenance, and generally undegraded performance with use. Reliability encompasses failure free performance in the usual sense and the ability to hold performance with environmental stress, i.e., launch vibration, temperature, etc.

A burden matrix was established for each of the systems, Tables X-5 through 8, containing row entries for each of the six burden factors and column entries for each major functional block. The camera entries for the monochrome system are assigned unit value for each burden and all other entries are sized as a ratio to these unit values.

The camera is baselined as a silicon intensifier target (SIT) vidicon type of the same general design as the GCTA color camera. Ratios were established based on experience with this camera system and others designed and built at AED. Development and design costs are not included and the assumption is that several units of each functional block would be produced.

The color system assumptions include the existence of a scan converter with self contained storage and processing circuitry in a reasonable size electronics module. The color monitor is assumed to provide adequate resolution in the same format required for monochrome display, for both the color and stereo systems. Motorized convergence angle adjustment, included as part of the lens/optics entry is assumed for the stereo system.

Referring to the burden matrix tables, the final column contains the sum of the row entries which are in turn summed to form a total burden number, 21 for the monochrome system. The final column entries are retabulated, Table X-9, and a system burden ratio, based on the mean burden sum, established for each system. (This procedure is identical to that followed for the

TABLE X-5. MONOCHROME SYSTEM BURDEN FACTORS

BURDEN	CAMERA	LENS/ OPTICS ASSY	PAN/ TILT	CONTROL	PROC	DISPLAY	Σ
Cost	1.0	0.10	0.50	.25	.15	0.40	2.4
Weight	1.0	.25	.90	.70	.45	1.40	4.7
Volume	1.0	.25	1.90	.60	.50	1.70	6.0
Power	1.0	.20	.65	.55	.40	1.35	4.2
Maintainability	1.0	.1	.2	.1	.1	.3	1.8
Reliability	1.0	.1	.3	.1	.1	.3	1.9
							21.0

TABLE X-6. COLOR SYSTEM BURDEN FACTORS

BURDEN	CAMERA	LENS/ OPTICS ASSY	PAN/ TILT	CONTROL	PROC	SCAN CONV	DISPLAY	Σ
Cost	1.0	.15	.50	.25	.15	.70	.50	3.3
Weight	1.0	.35	.90	.70	.45	.75	1.45	5.6
Volume	1.0	.25	1.90	.60	.50	1.00	1.70	7.0
Power	1.0	.35	.65	.55	.40	1.00	1.45	5.4
Maintainability	1.0	.1	.2	.1	.1	.2	.3	2.0
Reliability	1.0	.2	.3	.1	.1	.2	.3	2.2
								25.5

TABLE X-7. STEREO SYSTEM BURDEN FACTORS

BURDEN	CAMERAS*	LENS/ OPTICS ASSY	PAN/ TILT	CONTROL	PROC	DISPLAY WITH HOOD	$\sum$
Cost	2.05	.20	0.70	.30	.25	.50	4.2
Weight	2.45	.50	1.10	.90	.65	1.50	7.1
Volume	2.40	.50	2.25	.70	.60	2.50	9.0
Power	2.35	.40	.75	.65	.55	1.45	6.2
Maintainability	2.1	.2	.2	.1	.1	.3	3.0
Reliability	2.1	.2	.3	.1	.1	.3	3.1
							32.6

*Includes motorized convergence adjust mechanism.

TABLE X-8. TWO-VIEW SYSTEM BURDEN FACTORS

BURDEN	CAMERA	LENS/ OPTICS ASSY	PAN/ TILT	CONTROL	PROC	DISPLAY	$\sum$
Cost	2.0	.20	1.00	.30	.25	.80	4.6
Weight	2.0	.50	1.80	.90	.65	2.80	8.7
Volume	2.0	.50	3.80	.70	.60	3.40	11.0
Power	2.0	.40	1.30	.65	.55	2.70	7.6
Maintainability	2.0	.2	.4	.1	.1	.6	3.4
Reliability	2.0	.2	.6	.1	.1	.6	3.6
							38.9

performance effectivity described previously). This burden ranking appears to favor volume and weight as compared to cost so the weightings were modified to give equal weight to each row entry for the monochrome system.

The new tabulation is shown in Table X-10, where each column is given as the ratio to a unity assignment for the particular burden of a monochrome system. This manipulation produced surprisingly little effect, the relative burden factors for each system being substantially unchanged from those listed in Table X-9. The values listed in Table X-10 are used in the following discussion of performance versus burden weighting.

D. Performance/Burden Weighting

The relative importance assigned to burden factor as opposed to system performance will determine the system selected for remote operations. If it is assumed that clear view of the work volume is obtainable from a single camera location and that burden factors must be minimized, the monochrome system with a burden ratio of .7. should be selected. If on the other hand, performance is demanded and burden factor is relatively less important, then the two view system with a performance ratio of .73 should be selected.

This effect is illustrated by Figure X-5 where the mean of burden ratio to the weighted performance ratio is plotted for each system. By way of example, if burden and performance carry equal weight, $N = 1$, the monochrome and color system overall ratio is .975 while the other systems are unity for stereo and 1.055 for the 2-view system. This plot also demonstrates that except for narrow ranges of performance/burden ratio the choice of the color or stereo system is unattractive. Based on this process the monochrome system would be recommended for $N < 1.0$ and the two view system for $N > 2.0$. The tabulation shown in Table X-11 carries precise values of system rankings for specific values of N between 0 and 10.

TABLE X-9. SUMMATION AND SCALED BURDEN FACTORS

BURDEN	TV SYSTEM			
	MONO	COLOR	STEREO	2 VIEWS
Cost	2.4	3.3	4.2	4.6
Weight	4.7	5.6	7.1	8.7
Volume	6.0	7.0	9.0	11.0
Power	4.2	5.4	6.2	7.6
Maintainability	1.8	2.0	3.0	3.4
Reliability	1.9	2.2	3.1	3.6
TOTAL	21.0	25.5	32.6	38.9
SCALED	.71	.86	1.11	1.32

TABLE X-10. BURDEN FACTORS NORMALIZED TO EQUAL WEIGHT BASED ON MONOCHROME SYSTEM WITH SCALED SUMMATION

BURDEN	TV SYSTEM			
	MONO	COLOR	STEREO	2 VIEWS
Cost	1.0	1.38	1.75	1.92
Weight	1.0	1.19	1.51	1.85
Volume	1.0	1.17	1.50	1.83
Power	1.0	1.29	1.48	1.81
Maintainability	1.0	1.11	1.67	1.89
Reliability	1.0	1.16	1.63	1.90
TOTAL	6.0	7.29	9.54	11.20
SCALED	.71	.86	1.12	1.32

TABLE X-11. MEANS OF WEIGHTED PERFORMANCE AND BURDEN

SYSTEM	UNWEIGHTED		BURDEN + N x PERFORMANCE							
	B	P	B+.5P	B+P	B+1.5P	B+2P	B+2.5P	B+3P	B+5P	B+10P
Monochrome	.71	1.24	.887	.975	1.028	1.063	1.089	1.108	1.152	1.192
Color	.86	1.09	.937	.975	.998	1.013	1.024	1.033	1.052	1.069
Stereo	1.12	.88	1.040	1.000	.976	.960	.949	.940	.920	.902
2 Views	1.32	.79	1.143	1.055	1.002	.967	.941	.923	.878	.838

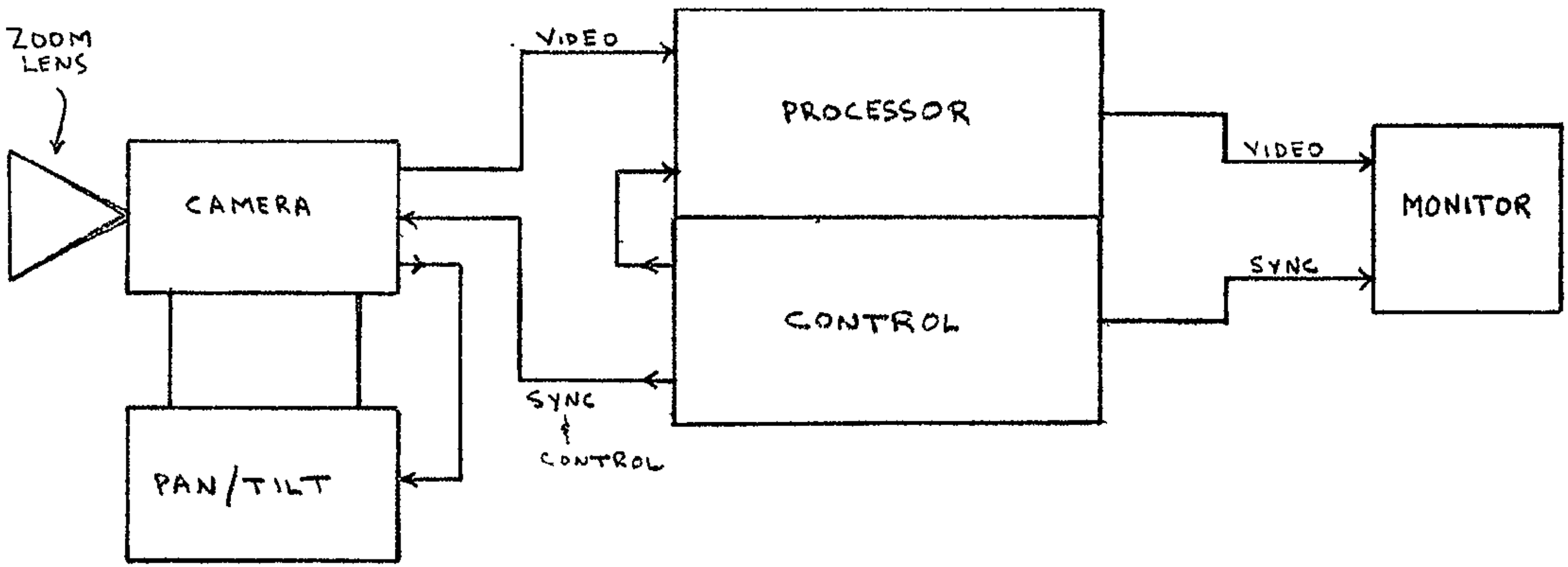

Figure X-1. Monochrome System Functional Block Diagram

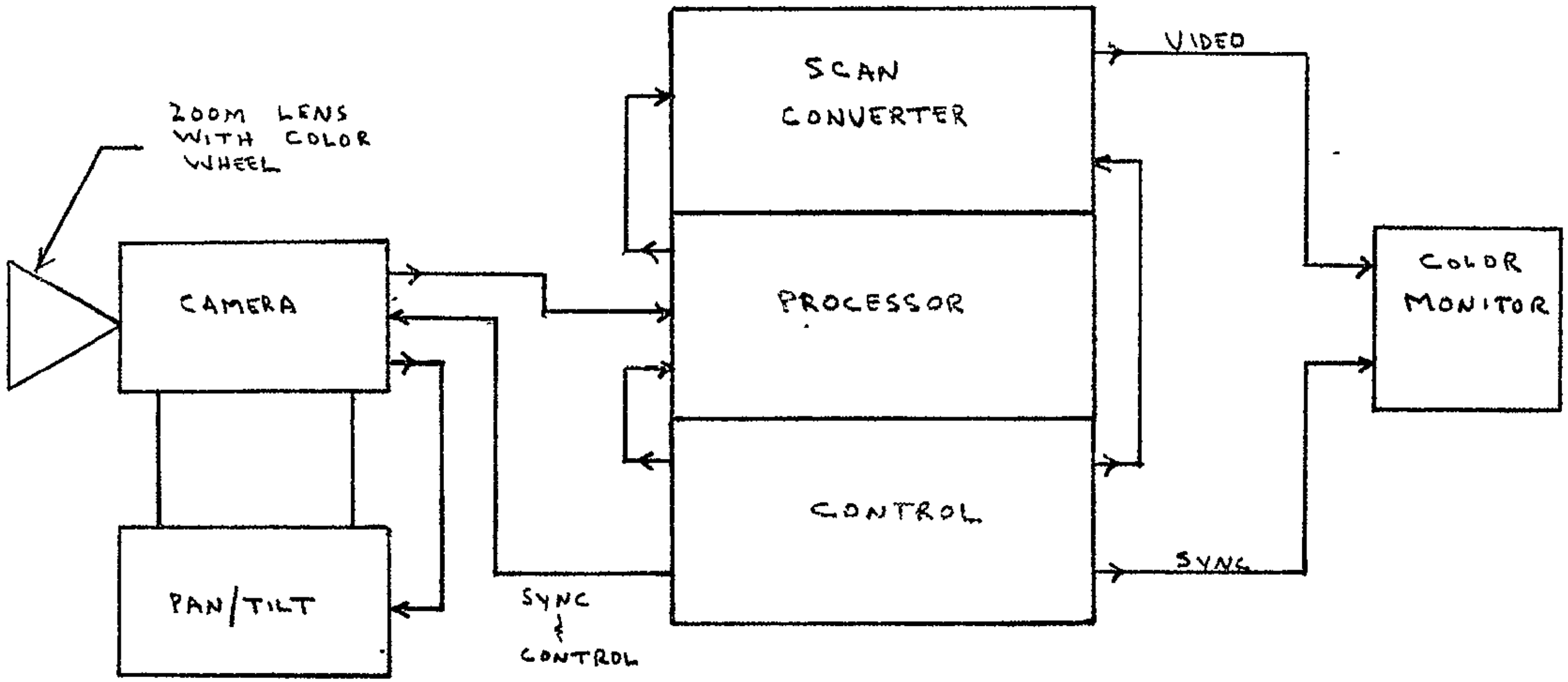

Figure X-2. Color System Functional Block Diagram

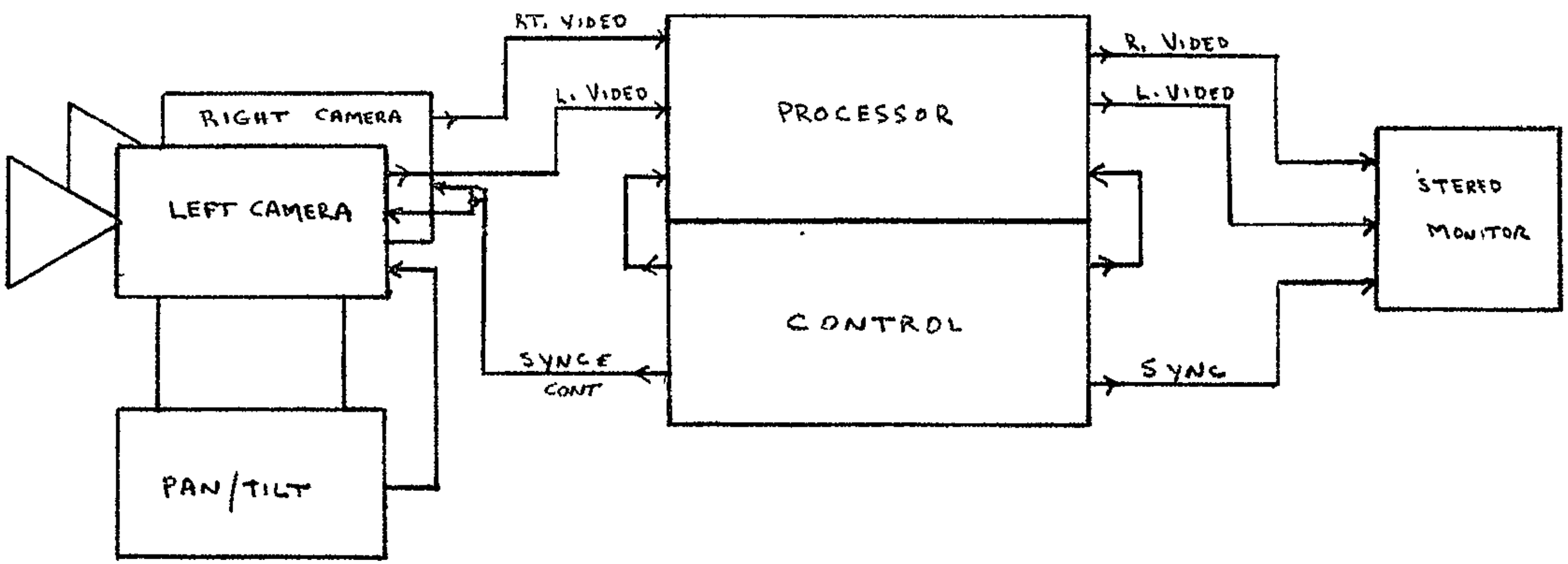

Figure X-3. Stereo System Functional Block Diagram

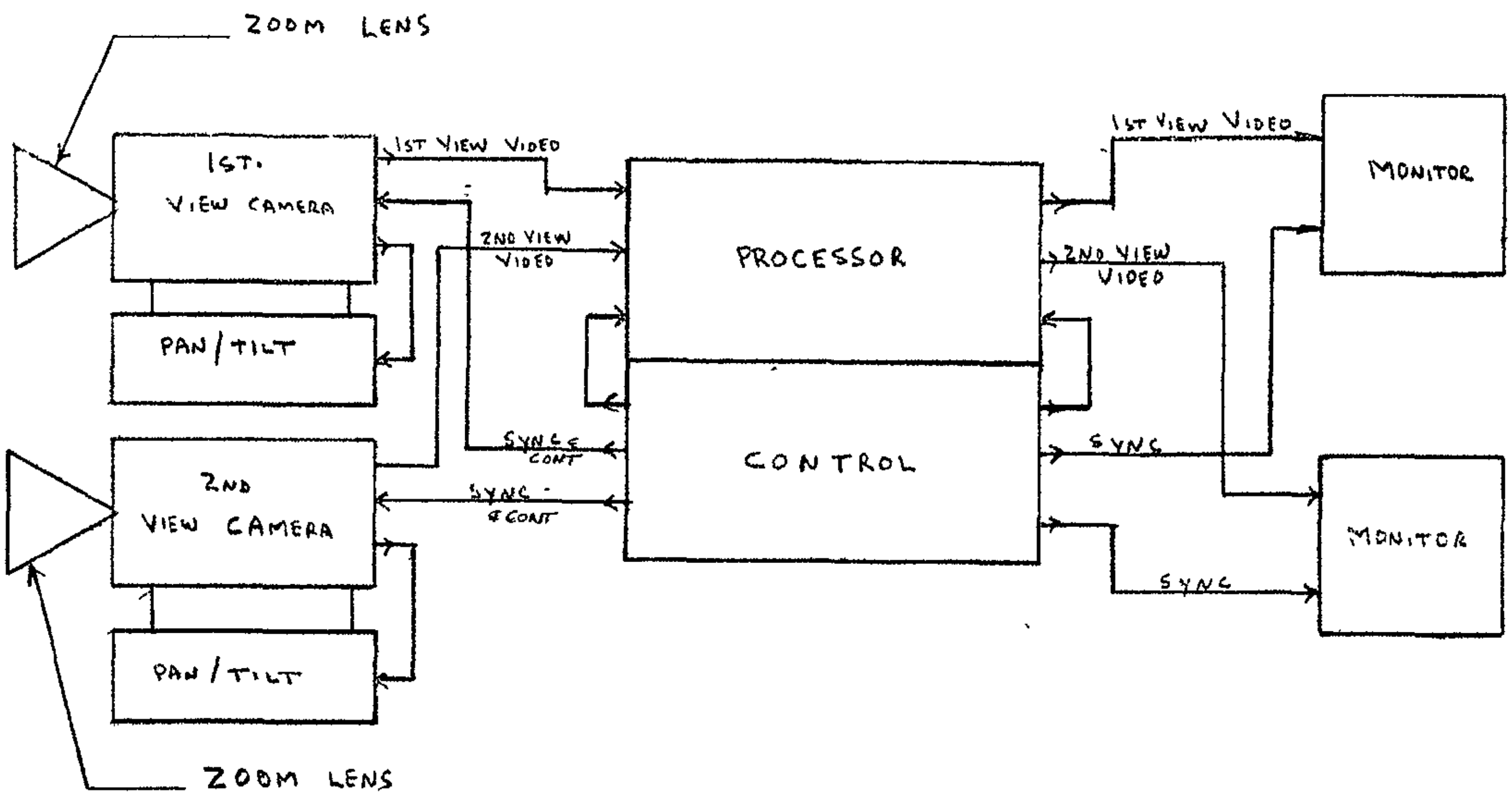

Figure X-4. Two-View System Functional Block Diagram

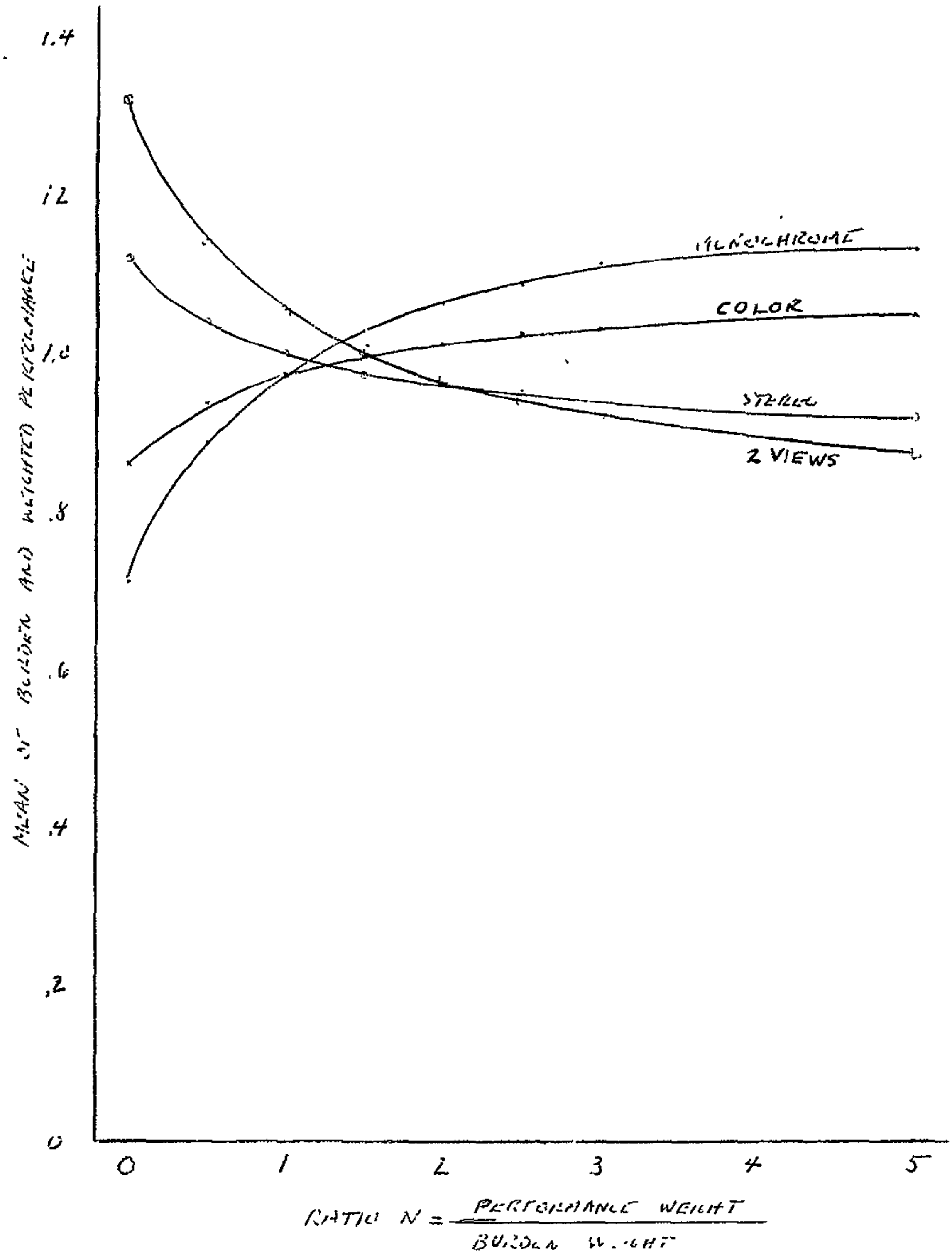

Figure X-5. Effect of Varying Ratios of Performance to Burdens

XI. CONCLUSIONS AND RECOMMENDATIONS

The simulator testing conducted during this program has generated a substantial quantity of performance data. The results, supported by statistical analysis, have shown that differences among systems and work tasks are substantially more significant in influencing performance than parameter differences. The influence of object differentiation depth precision, reference, and dynamics appears to be amenable to training, and even under relatively adverse combinations of parameters, performance is not strongly influenced.

Two levels of resolution, differing by a fairly substantial amount were used during the first test series. The overall results do not indicate a substantial difference in performance. Differences in accuracy were noted, however, with all but the monochrome system showing an accuracy reduction roughly in proportion to the resolution reduction (for two repetitions). The monochrome system accuracy was unexpectedly poorer at high resolution, apparently attributable to 3 data points having combinational parameters resulting in low accuracy.

The overall results of the simulation testing indicate that for a combination of remote operations there will be a performance advantage for the 2 view system as compared to the other systems. On the combined effectivity scale, rating each task at equal importance, this system rates at .79 as compared to .88 for stereo, 1.09 for color and 1.24 for monochrome. Thus a monochrome system would result in about a 50 percent decrease in effectivity as compared to the 2 view system.

Based on a similar burden scale constructed of overall cost, weight, volume, etc., the monochrome system shows to advantage with a burden factor of .71. For this characterization the order of preference is reversed as compared to the effectivity scale, ranking at .86 for color, 1.12 for stereo, and 1.32 for 2 views.

The relative importance of performance as compared to burden may well depend on the mission for which the remote operations system will be employed. Even after selection of the application (mission) profile, the assignment of relative importance to these scaled parameters may be expected to be controversial.

This controversy is likely to evaporate if a relatively complicated array of operations are required for a particular application. If the remote operations contemplated for the Space Shuttle are considered, for example, one may expect some objects, bulkheads, or equipment segments to be interposed between some points of interest and any particular fixed camera location. A multiplicity of camera views will then be required to implement the required operations and the burdens accruing to the 2 view system are largely eliminated. It would then appear that the availability of two monitors, and perhaps somewhat more complex command and switching capability, are required, certainly not substantial burdens as compared to the total.

The overall system recommendation, then, is that a two view system, of the form shown in Figure X-1, be employed for the general application of remote operations with television. The system is configured assuming a single operations location, and may be expanded to include several locations. For additional locations, one or more additional cameras allowing direct line of sight by two cameras offset, in general, by 75 to 90 degrees is assumed.

The cameras will be equipped with zoom lenses with sufficient range to provide an overall perspective of the work area within the short focal length extreme and adequate detail within the long focal length extreme. Detail will generally be adequate when the smallest element of interest is represented by about

3-to-5 picture elements. Travel time between the two extremes should be short so that perspective information is retained by the operator after the close-up view is available.

Iris and focus lens controls are available and, as for the zoom, will be adjustable from the operator control station. Generally, scene illumination should be such that the iris is several f-stops down from maximum to provide good depth of field. Focus adjustment will not be critical, then, and repeated tweaking will not be required.

Changes in light level will be accommodated by the camera with automatic adjustment of the ALC function. Depending on the scene, this function may be operated in the peak mode, to prevent highlight overload, or in the average mode, to permit better visibility of the darker portions of the scene.

Gamma correction is also incorporated in the video channel to improve visibility of darker areas of the scene. This type of circuitry "stretches" blacks and emphasizes noise so that high quality pre-amplifiers are required.

The cameras are mounted on pan/tilt units to permit pointing at the work volume and framing of the area(s) of interest on close-ups. Rates of motion are variable to permit rapid adjustment and accurate settings where alignment aids are used.

All remote adjustments are made by the operator at a control panel. Control signals issued by the operator are encoded and multiplexed with master sync signals in the controller electronics. These are fed to the cameras via a video coax line (one line per camera) where they are separated and decoded for implementation of the control information.

The video signal from the camera is fed via coax line to the processor unit. The processor incorporates the functions of line equalization, video switching and routing, and distribution amplification. In general, a multiplicity of cameras will be used two at a time with the appropriate video selected and routed to either of the two monitors.

The monitors are mounted in front of the operator at a distance permitting visual observation with no less than 2 minutes of arc per picture element. At a viewing distance of 20 inches, a 9-inch monitor is employed. Adjustable brightness to at least 100 foot-lamberts is provided, with spot size no larger than 0.7 of the scan line pitch to provide essentially full reproduction of the video signal.

APPENDIX A

EXPERIMENT I INPUT DATA FOR 2-REPETITION MEANS

#	S	TRIAL	EFFECT	X	Y	Z	Θ	TIME	CONTACT-SEC.	RANK
1	6	12	GRAND	.02	0	.05	3.07	157	4.5	6
2	4	3	A	.03	.03	.07	3.59	150.5	5.7	18
3	7	8	B	.03	.03	.015	3.11	263	109.8	18
4	2	6	AB	.047	0	.031	5.101	177	1.2	11
5	8	8	C	.03	0	.05	2.58	131	2.7	20
6	1	11	AC	.047	0	.015	2.07	555	0	20
7	5	15	BC	.06	.015	.015	4.62	154.5	15	4
8	3	14		.03	0	.03	2.94	87	7.2	9
9	4	2	D	.02	.05	.03	1.54	553	54.9	3
10	6	3	AD	.03	.25	.02	9.93	120.5	8	1'
11	2	3	BD	.047	0	.031	.982	219.5	0	9
12	7	4	FHJ, BLOCKS	.05	.03	0	4.61	214.5	93	12
13	1	8	CD	.031	0	.031	.398	96	0	14
14	8	9	ACD	.02	.03	.03	5.63	238	3	20
15	3	11	BCD	0	0	.05	4.45	306	2.4	1:
16	5	8		.015	.015	0	2.82	221	.3	18
17	3	8	E	.03	.38	.05	3.57	82.5	0	10
18	5	7	AE	.03	.03	0	4.13	159.5	1.2	16
19	1	14	BE	0	.03	.015	1.431	195	1.75	5
20	8	2		.06	.14	.03	7.12	285.5	13.5	19
21	2	5	CE	.0625	0	.016	7.123	76.5	0	10
22	7	13		.015	.08	.015	.53	87.5	24	12
23	4	6		.05	.03	.015	5.63	162.5	26.4	19
24	6	9	GJ	.02	0	.05	2.33	113.5	.6	12
25	5	14	DE	.05	.07	0	2.08	239	84	14
26	3	4		.031	0	.0625	4.1	122	8.1	5
27	8	11		.06	.10	0	6.15	212	0	20

c KEPS

#	S	TRIAL	EFFECT	X	Y	Z	Θ	TIME	CONTACT-SEC.	RANK
28	1	9		.031	0	.015	1.193	197	0	3
29	7	10	CDE	.05	0	.015	5.1	86	2.1	18
30	2	9		.031	0	.02	1.79	103.5	14.6	17
31	6	14		.02	0	.05	3.07	172.5	.6	20
32	4	16		0	.015	.015	2.58	134	1.5	20
33	3	16	H	.25	.39	0	1.36	94.5	4.5	11
34	5	6	AH	.1	.41	.03	1.15	98.5	2.7	7
35	1	15	BH	.172	1	0	1.29	127.5	9	2
36	8	1		.06	.30	.11	4.07	236	14.7	13
37	2	15	CH	.063	.14	0	1.12	120	16.2	8
38	7	11		.07	.13	0	1.65	92	0	17
39	4	9		.05	.27	0	.43	72	0	20
40	6	7		.19	.10	0	1.86	132	.9	12
41	5	11	DH	.03	.03	0	.93	87	13.2	14
42	3	13		.02	.50	.02	1.11	93	25.5	[illegible]
43	8	7		.05	.40	0	1.15	214	9.9	15
44	1	5	FJ	.219	.469	0	2.68	117.5	.3	7
45	7	12	CDH	.11	.28	0	1.86	84	0	19
46	2	14		.03	.05	0	0	107.5	4.2	9
47	6	11		.16	.02	0	.64	146	0	20
48	4	12		.11	.05	0	.93	86.5	5.4	20
49	6	13	EH	.15	.38	0	.43	127.5	8.1	8
50	4	5		.02	.32	0	1.15	91	1.5	17
51	7	2		.14	.14	0	1.83	131	26.4	12
52	2	8		.03	.08	0	.12	110.5	7.2	[illegible]
53	8	6		.02	.08	.10	.72	154.50	3	9
54	1	3		.03	.06	0	.7	50.5	0	[illegible]

2 REPS

#	S	TRIAL	EFFECT	X	Y	Z	Θ	TIME	CONTACT-SEC.	RANK
55	5	4		.07	.11	.31	2.22	108.5	0	15
56	3	3	GHJ	.19	.77	0	.44	131	0	18
57	4	14		.12	.22	0	1.65	76	10.8	19
58	6	2	BLOCKS	.13	.14	0	.92	99.5	1.5	17
59	2	2	BLOCKS	.03	.045	0	1.5	108.5	3.6	15
60	7	14		.30	1.16	.07	.14	118	0	3
61	1	12	FG	.078	.047	0	3.13	60.5	0	16
62	8	15		.07	0	0	1.15	95	1.2	20
63	3	1		.07	.13	0	.65	112.5	5.1	19
64	5	1		.1	.06	.03	4.71	314.5	45	9
65	8	3	J	.10	.50	.06	.40	207.50	8.4	19
66	1	10	AJ	.094	.297	.16	.008	92	12	1
67	5	5	BJ	.75	1.38	.63	0	118	6	4
68	3	12		.08	.47	.03	.48	182	17.2	3
69	6	6	CJ	0	2.32	.19	0	121	0	4
70	4	1		.80	1.02	.07	6.37	248	313.5	3
71	7	6	BLOCKS	.19	2.38	.32	1.74	162	74:70	3
72	2	13	EG	0	.29	.14	.04	197.5	15.4	8
73	1	4	DJ	.25	.312	.281	.995	174	0	2
74	8	10		0	.32	.05	.29	312	38.3	9
75	3	9		.08	.22	.02	.52	139.5	9.6	2
76	5	13	FH	.08	3	.75	.92	181	42.2	9
77	4	10	CDJ	.03	.08	.05	1.78	65	25.2	19
78	6	16		0	.16	.03	.40	96.5	0	11
79	2	12		0	.13	.09	.83	157	0	17
80	7	1		.07	.50	.16	.41	147.5	36	4
81	2	11	EJ	.19	.33	.09	3.07	112	22.8	14

2 REPS

#	S	TRIAL	EFFECT	X	Y	Z	Θ	TIME	CONTACT-SEC.	RANK
82	7	9		.05	.59	.08	.13	120.50	9.9	3
83	4	7		.03	.17	.19	.01	150	48	19
84	6	5	CG	.03	.35	.03	.19	111.5	11.7	19
85	3	7		.08	.24	.05	.65	182	12.3	6
86	5	16	BG	.14	.35	.22	.80	78	18.6	13
87	1	6	AG	.093	.031	.094	.01	156.5	0	13
88	8	13	G	0	.02	0	.60	279	74.5	20
89	7	5		.13	.86	.08	.92	131.5	105.3	3
90	2	16		0	.02	.02	1.59	140	.9	14
91	6	8	BLOCKS	.07	.66	.14	.48	215	0	8
92	4	13	CDG	.25	.32	0	1.59	97	47.40	17
93	5	12		.05	.03	.05	.74	138	7.9	16
94	3	2		0	.09	.031	.52	136	8.4	11
95	8	5		0	.06	.02	.29	302.5	42	20
96	1	7	DG	.093	.062	.078	.496	148.50	1.8	15
97	2	7	HJ	0	.29	0	3.23	131.50	9	9
98	7	15	AHJ	0	.22	0	.17	128.50	4.2	5
99	4	8	BHJ	.015	.22	0	.92	133	15	20
100	6	10	DF	.05	.38	0	1.78	177.5	0	15
101	3	10	CHJ, BLOCKS	.10	.32	0	3.95	110	9.6	9
102	5	3		.05	.08	0	.75	114	1.2	13
103	1	2		0	.299	.015	.9	190.5	11.1	14
104	8	4	CDF	.10	.18	0	1.166	313.5	10.2	15
105	7	7	DHJ	.05	.36	0	2.18	176	72	17
106	2	1	BF	.03	.18	0	4.115	189	496.2	5
107	6	15	AF	.05	.31	0	1.95	166	36.90	1
108	4	4	F	.03	.12	0	.92	191.5	1.1	12

6 REPS

#	S	TRIAL	EFFECT	X	Y	Z	Θ	TIME	CONTACT-SEC.	RANK
109	5	2	CDHJ	.43	.05	0	2.81	190	15	6
110	3	5		.03	0	0	1.29	175	18.3	11
111	8	14		.032	.03	0	.54	223.5	39.6	19
112	1	13	CF	0	0	0	0	164	24	15
113	8	12	EHJ	.15	.66	0	2.18	196	5.1	18
114	1	1		.094	.26	0	.2	148.5	6	8
115	5	10		.03	.02	0	.93	87	13.2	13
116	3	6		.11	.17	0	1.43	3320	217.5	4
117	6	4		.08	.05	0	.52	118	3.6	6
118	4	15		0	.15	0	.52	2050	1.5	19
119	7	3		.02	.03	0	1.26	167	9.6	4
120	2	4	GH	.016	.14	0	.70	[illegible]	[illegible]	15
121	1	16		0	[illegible]	0	.172	140	47.5	7
122	8	16		.02	.14	0	.53	144	3.6	20
123	3	15		.14	.16	0	.34	244.5	47.7	9
124	5	9	EF	.015	.03	0	.34	340	9	7
125	4	11		.015	.05	0	.34	111	20.7	20
126	6	1		.16	.03	0	1.09	166	38.1	10
127	2	10		.016	.033	0	1.07	220	2	11
128	7	16	BLOCKS	.09	.05	0	.35	254.5	0	12
⋮										

APPENDIX B

CONTRIBUTIONS OF INDEPENDENT VARIABLES TO TASK PERFORMANCE FOR FIRST TEST SERIES

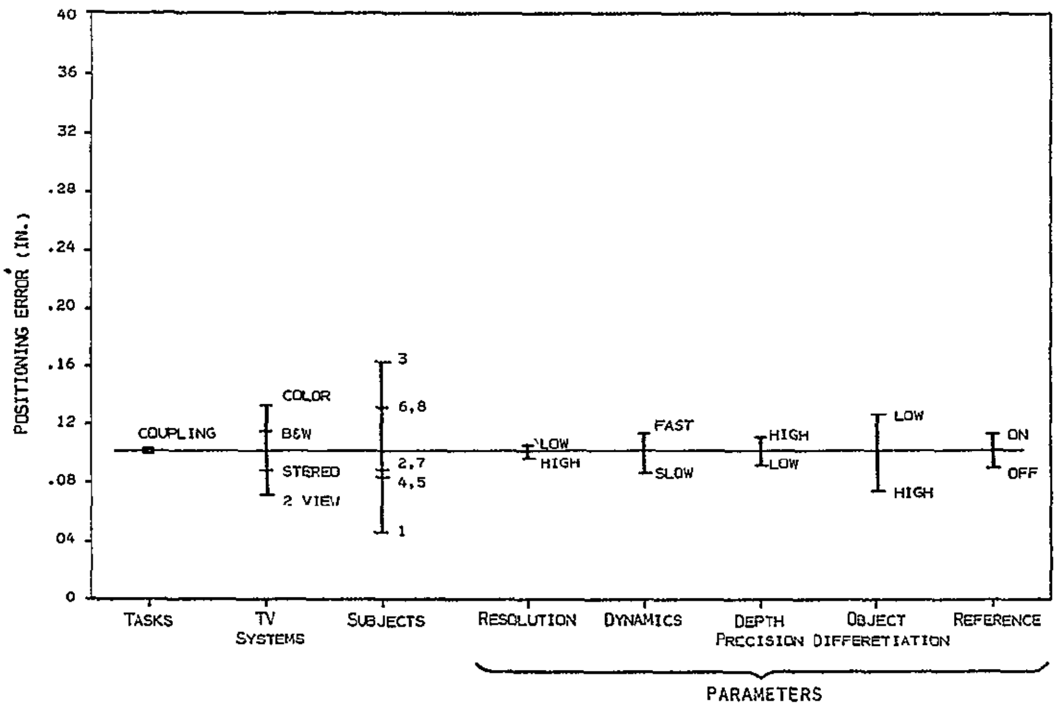

Figure B-1. Contributions to Positioning Error for Coupling Task

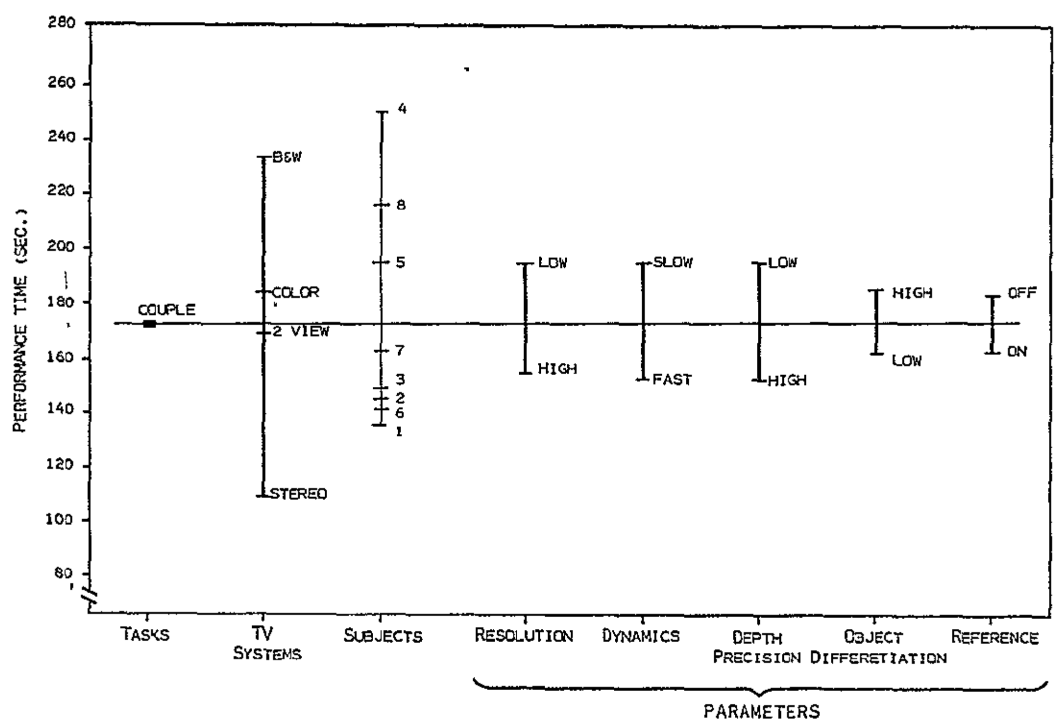

Figure B-2. Contributions to Performance Time for Coupling Task

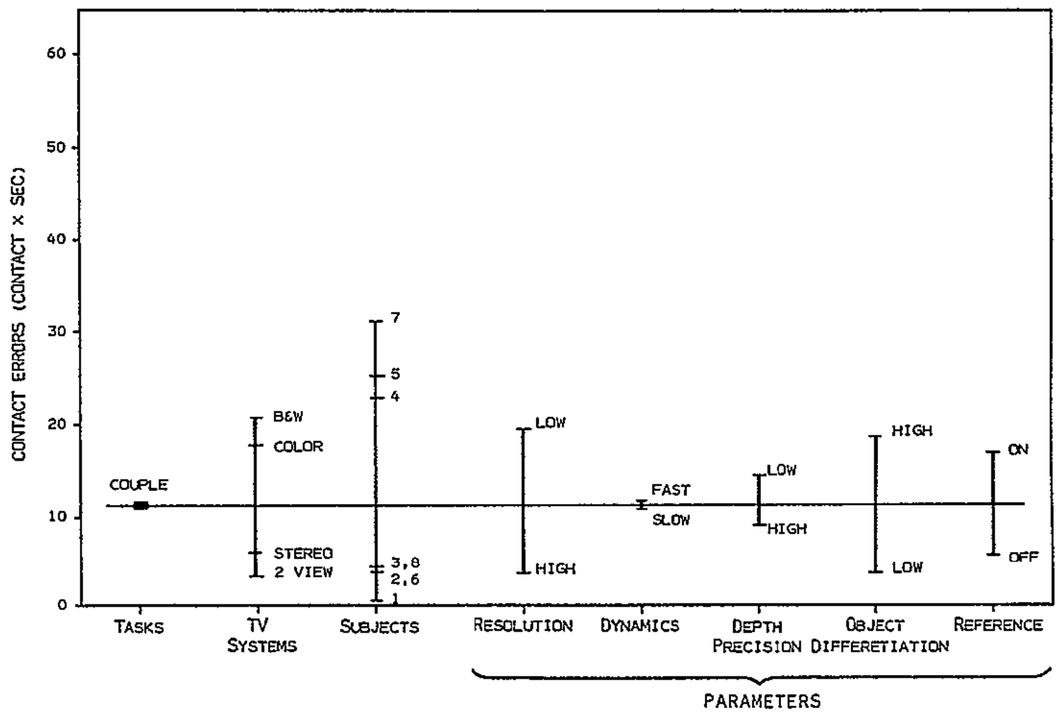

Figure B-3. Contributions to Contact Error for Coupling Task

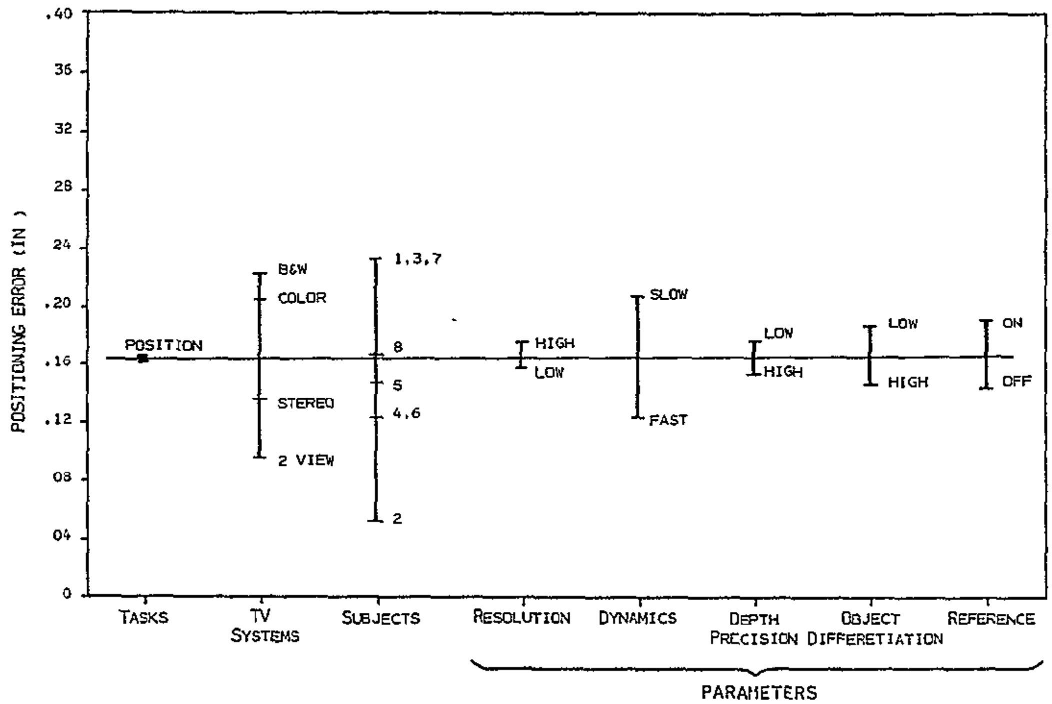

Figure B-4. Contributions to Positioning Error for Precise Positioning Task

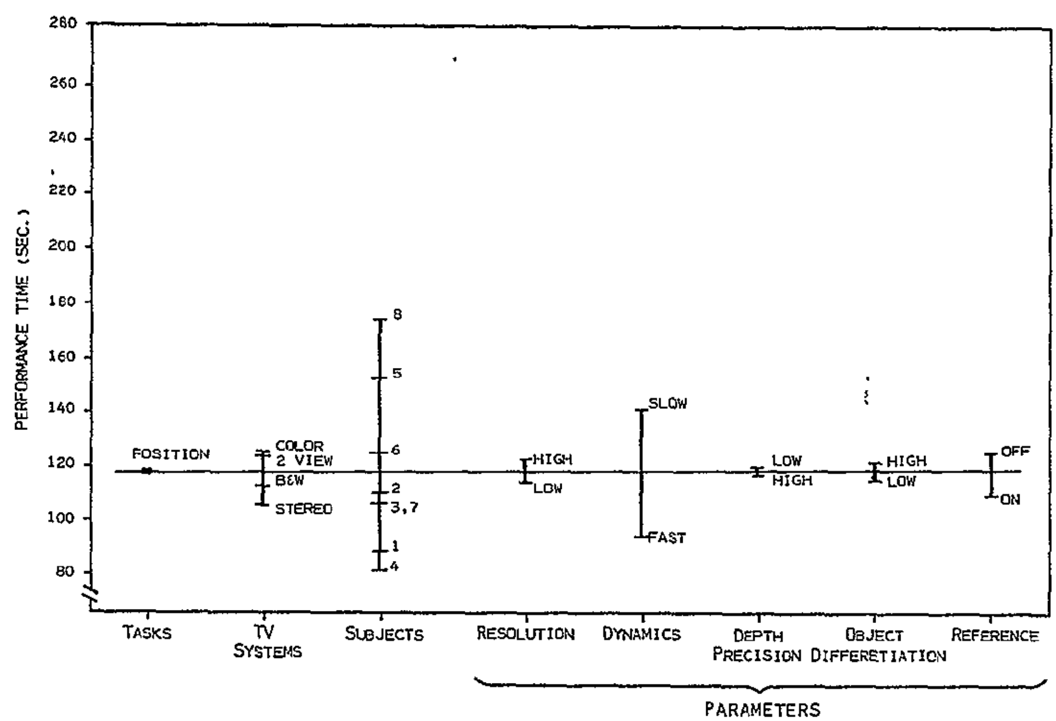

Figure B-5. Contributions to Performance Time for Precise Positioning Task

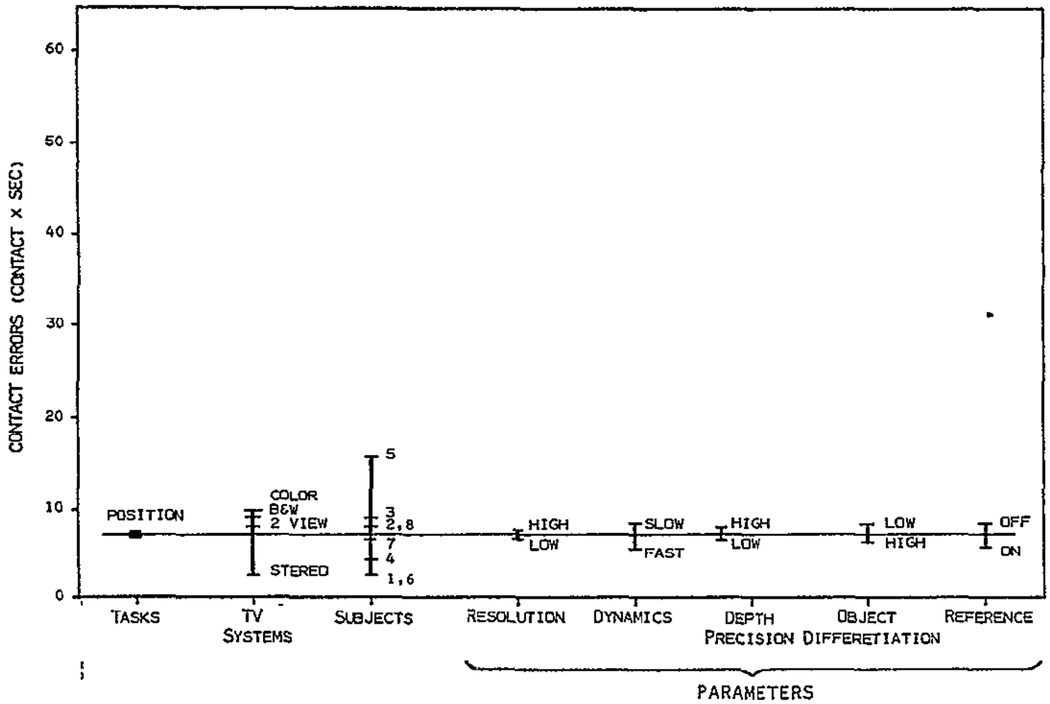

Figure B-6. Contributions to Contact Error for Precise Positioning Task

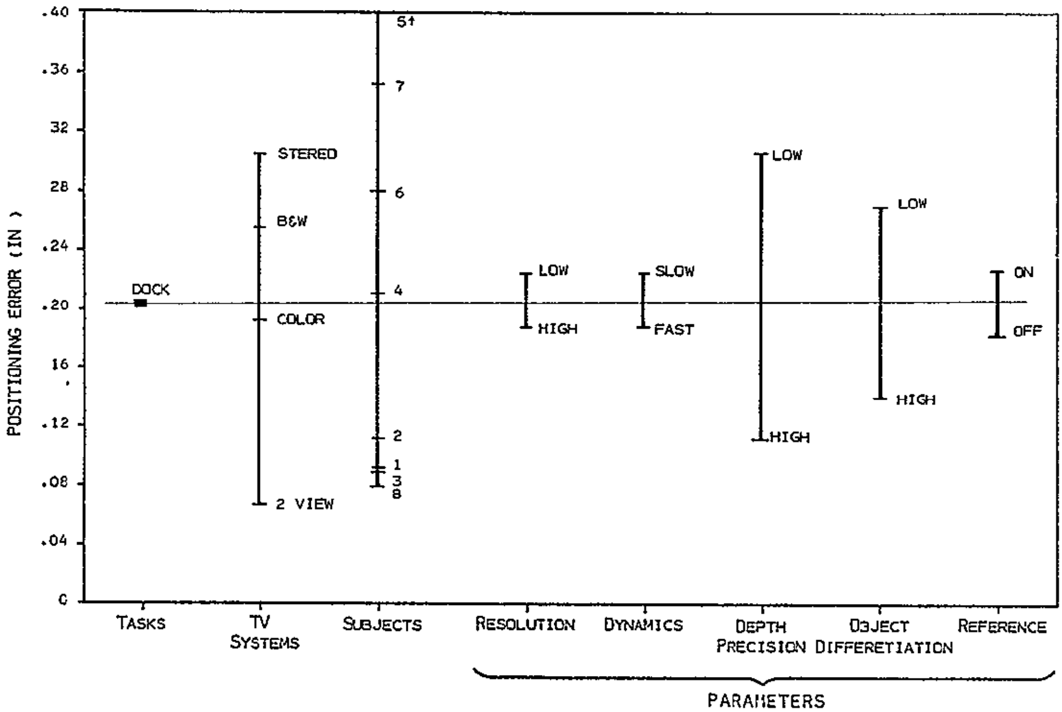

Figure B-7. Contributions to Positioning Error for Docking Task

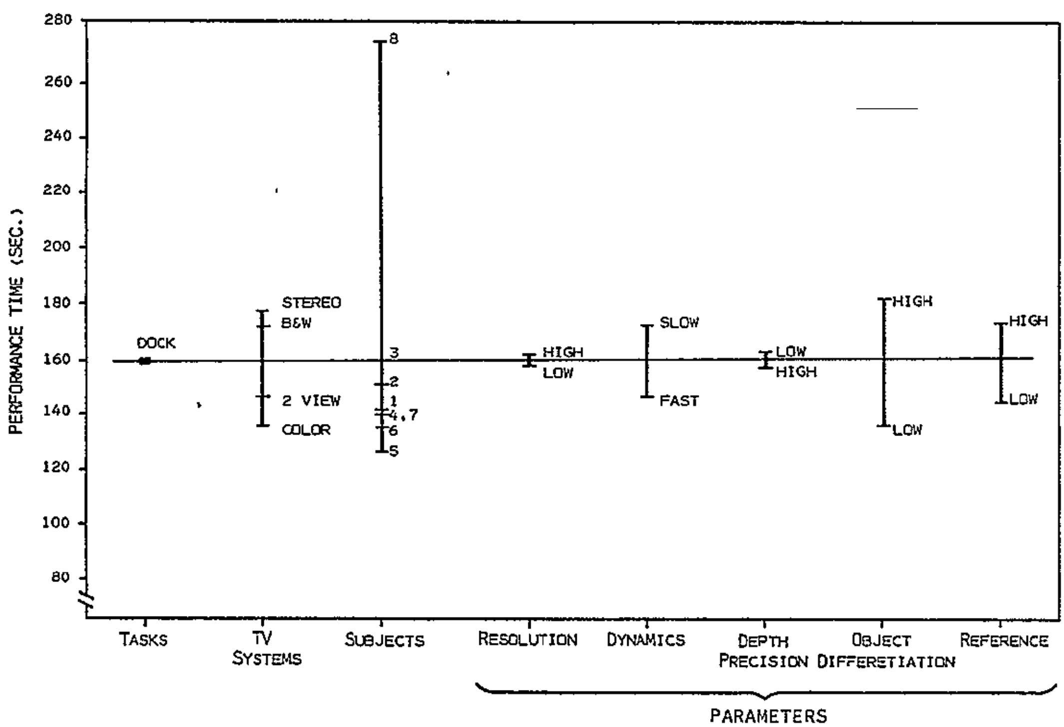

Figure B-8. Contributions to Performance Time for Docking Task

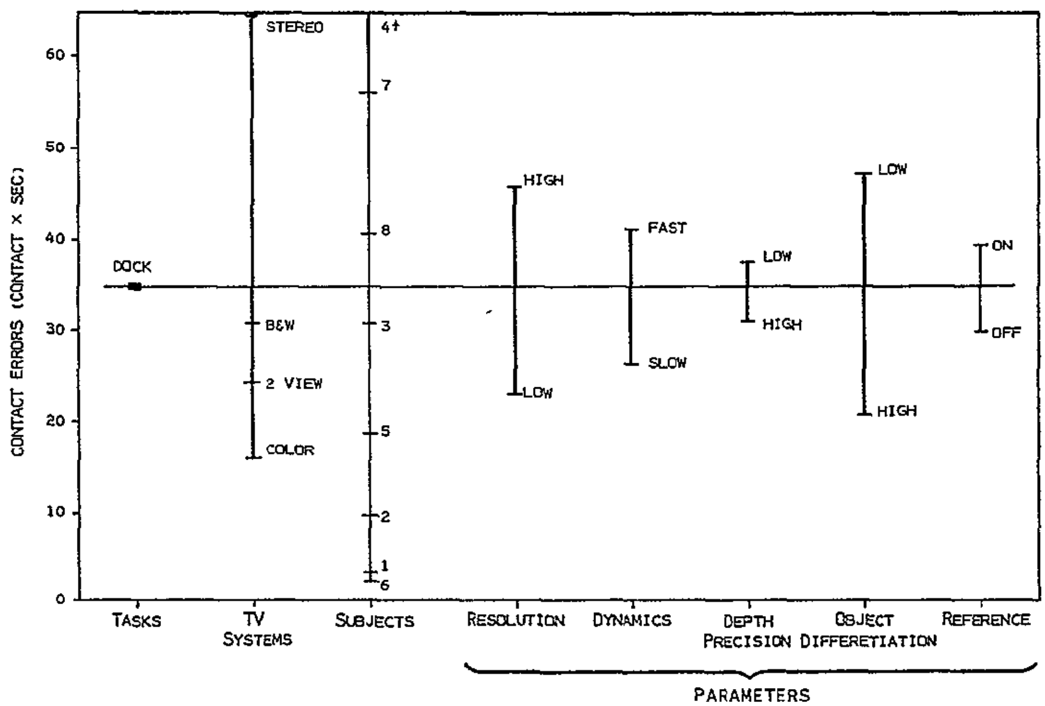

Figure B-9. Contributions to Contact Error for Docking Task

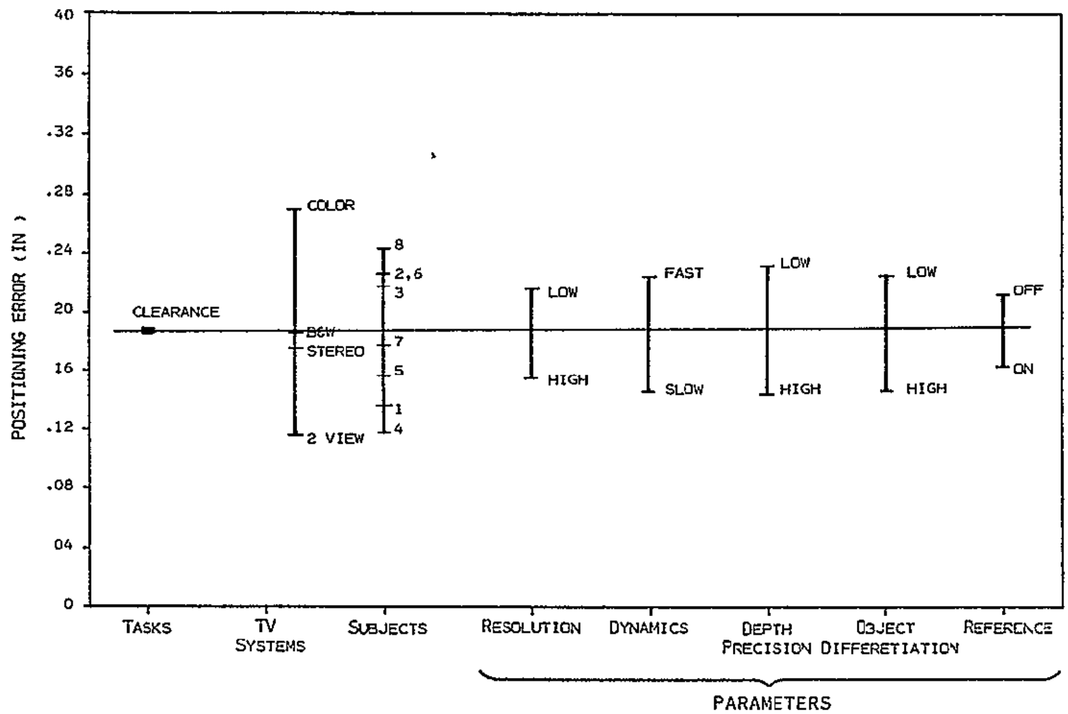

Figure B-10. Contributions to Positioning Error for Clearance Task

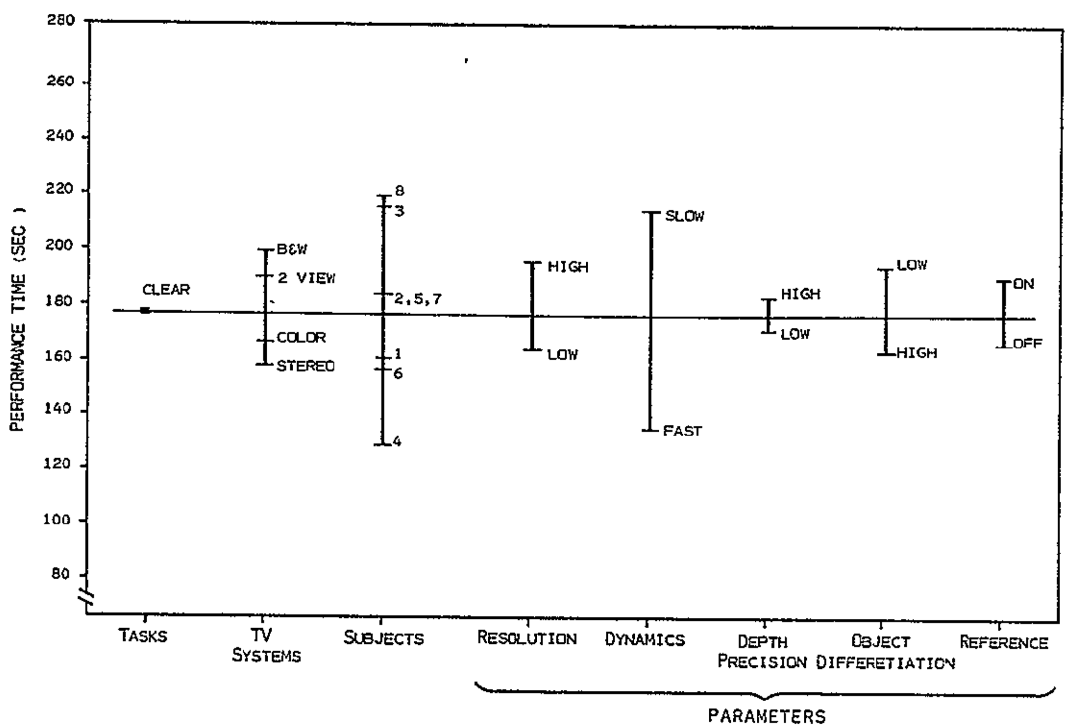

Figure B-11. Contributions to Performance Time for Clearance Task

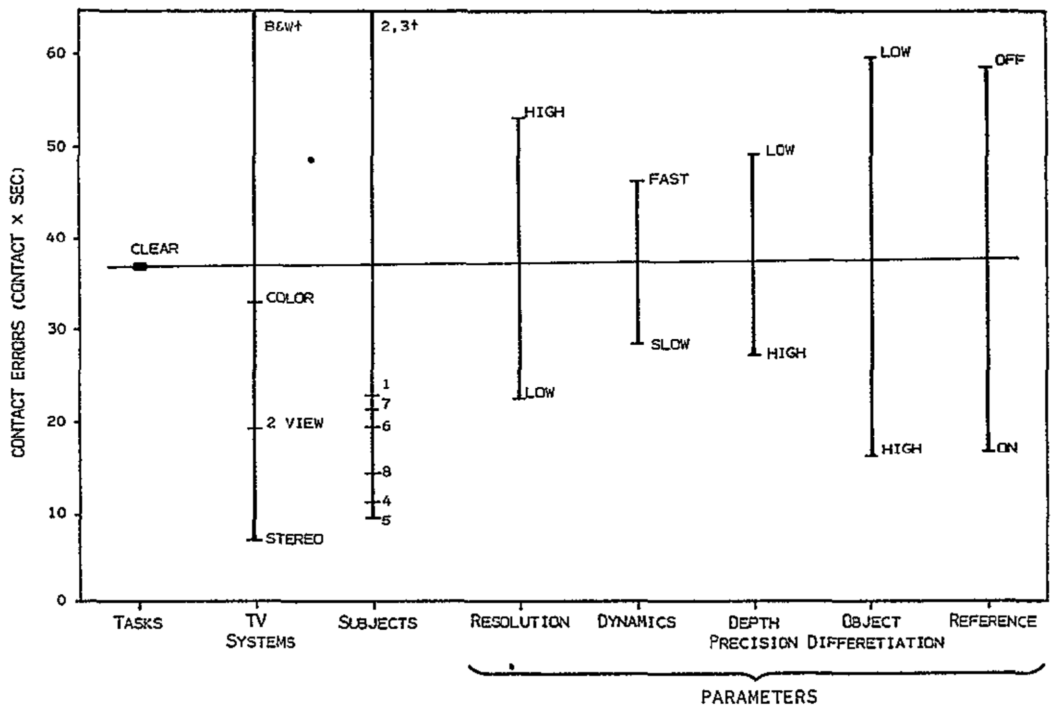

Figure B-12. Contributions to Contact Error for Clearance Task

APPENDIX C

EQUIPMENT SPECIFICATION

SPECIFICATION

FOR

A TELEVISION SYSTEM FOR CONTROLLING PAYLOAD AND EXPERIMENT OPERATIONS

SPECIFICATION

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C. EQUIPMENT SPECIFICATION

1. SCOPE

This Specification is intended to define the characteristics of the TV system recommended for spacecraft use to control payloads and experiments. The specified two-view monochrome system was selected as a result of analyses, tests, and trade-off studies. The specification deals with the major elements of the equipment, including physical characteristics and major electrical interface requirements.

2. GENERAL REQUIREMENTS

The two-view system is intended to provide television coverage of remote operations. Therefore, the equipment shown in block form in Figure IV-1 is divided into local and remote segments The cameras and pan/tilt units are remote from the operator controlling the operation, while the monitors, control unit and processor are located in the immediate vicinity of the operator. While the general installation may consist of two or more two-view camera set-ups, it is assumed that only the control unit and processing complexity would be affected, and the specified characteristics of this document would be largely unaffected.

3. TV CAMERA

3.1 General. The camera consists of a sensor assembly and a zoom lens, attachable without disassembly of the sensor assembly. The lens contains motors and drive provisions to permit adjustment of focal length (zoom), iris, and focus. The sensor assembly consists of the light sensitive device together with scanning, signal amplifying and processing circuitry; synchronizing, timing, and decoding circuitry; and power supply and conditioning circuits.

3.2 Physical Requirements

3.2.1 Mechanical. The camera, excluding lens, shall occupy a volume no larger than 5 x 7 x 13 inches and shall weigh a maximum of 11 pounds. The lens shall be attachable via a quick disconnect arrangement; a single electrical connector shall be employed for lens adjust motor drives. The nominal zoom lens is estimated to add no more than 3 pounds and 5 inches to the 13-inch long sensor assembly.

3.2.2 Optical. The zoom lens shall have a focal length range of from 15-to-150 millimeters corresponding to an angular width-of-view of 46-to-4.8 degrees. The open iris lens relative aperture shall be f/2.5 or smaller. A minimum aperture range of 30-to-1 shall be obtainable via the iris adjustment.

3.2.3 Modularity. The camera shall be designed with a high degree of modularity to permit replacement of elements with a minimum of set-up and adjustment. The lens assembly in particular shall be replaceable from the exterior of the camera case and will require no adjustment, other than focus, to achieve normal operation.

3.3 Functional Requirements

3.3.1 Scan

3.3.1.1 Direction. The camera scan will be in a direction such that the scene will be readout top-to-bottom and left-to-right as the scene is viewed.

3.3.1.2 Scan Line Rate. The scan rate (horizontal rate) will be nominally 15,734 scan lines per second. Phase and frequency lock to the externally provided sync signal will be maintained.

3.3.1.3 Field Scan Rate. The field scan rate (vertical rate) will be 1/262.5 of the horizontal rate or about 59.94 fields per second. Phase and frequency lock to the externally provided sync signal will be maintained.

3.3.1.4 Scan Lines. There will be 262.5 scan lines per field resulting in 525 interlaced scan lines per frame, with a frame defined as two successive fields.

3.3.1.5 Aspect Ratio. The total area occupied by the picture will consist of four units of horizontal dimension and three units of vertical dimension, an aspect ratio of 4:3.

3.3.1.6 Scan Rate Tolerance. Refer to Federal Communications Commission standards for synchronization.

3.3.1.7 Blanking Intervals. Refer to waveforms in reference 3.3.1.6.

3.3.2 Camera Video Output

3.3.2.1 Polarity. The video polarity, defined as the potential of a black area of a scene relative to a white area, shall be black negative.

3.3.2.2 Impedance. The standard load impedance on the single-ended video line shall be a nominal 75 ohms. The output impedance of the video line shall be constant to within ±5 percent over the useful video band.

3.3.2.3 Composite Signal. The composite video is the signal resulting from the combination of video and synchronizing (sync) signals. (The location of the combining of the sync to the video signal, internal to the camera or in the processing equipment, is not constrained by the camera operation. The description of the video level is given with the presumption that the signal is composite at the camera output.)

3.3.2.4 Levels. The blanked picture signal with setup, as measured from blanking-to-peak-white across the standard load impedance, shall be 0.714 $\pm$0.1 volt (100 IRE units). The sync signal shall be 0.286 $\pm$0.05 volt (40 IRE units). The standard setup is 7.5 $\pm$5 IRE units. The composite signal, then, is nominally 140 IRE units from sync-tip to peak-white. (See document 58 IRE 23.51 for method of measurement.)

3.3.3 Controls

3.3.3.1 Camera Identification. The camera identification and control information will be fed to all cameras on the sync line. The camera controls will operate only when the particular camera is addressed. The particular camera code number will be established prior to installation, and after removal may be changed by simple adjustment such as via plug-in board replacement or switch setting.

3.3.3.2 Power. The camera power control ON signal will result in the application of power to the camera (tentatively established as +24 to +33 volts dc). The power OFF signal will result in the removal of dc power and turn the camera off.

3.3.3.3 Automatic Light Control. Three-position control is required. The camera modes resulting from the three-position signal are ALC peak-Mode, ALC Average-Mode, and ALC Disable. The third control signal shall result in disabling the ALC feedback loop and allowing the sensor to operate with maximum sensitivity for any input light level.

3.3.3.4 Focus. Lens focus will be accomplished via this control. The control information will result in the lens focus motor rotating to accomplish a closer or farther focus position of the lens. The rate of focus adjustment will permit complete travel in 20 seconds.

3.3.3.5 Iris. Lens iris adjustment will be accomplished via this control. The control information will result in the lens iris motor rotating to open or clsoe the iris in response to the control information. The rate of iris adjustment will permit complete travel in 10 seconds.

3.3.3.6 Zoom. Lens field-of-view adjustment will be accomplished via this variable rate control. The control information will result in the zoom motor rotating to shorten or lengthen the lens focal length, at rates sufficient to encompass the complete zoom range in from 3-to-15 seconds.

3.3.3.7 Azimuth. This control information will be decoded by the particular camera being addressed and fed to the corresponding azimuth/elevation drive mechanism. The decoded information will contain direction (left or right) and rate information. Power for the azimuth drive circuitry (external to the camera) will be derived from, or controlled by, the camera circuitry and applied in response to the camera ON/OFF control signal.

3.3.3.8 Elevation. This control information will be decoded by the particular camera being addressed and fed to the corresponding azimuth/elevation drive mechanism. The decoded information will contain direction (up or down) and rate information. Power for the elevation drive circuitry, which is external to the camera, will be derived from, or controlled by, the camera circuitry and applied in response to the camera ON/OFF control signal.

3.3.3.9 Spares. Three additional control functions are assumed but not yet defined. These may include, for example, test signal ON/OFF or heater power ON/OFF. It is assumed that these signals are bi-level in nature.

3.4 Performance

3.4.1 Sensitivity. The camera shall be capable of providing an output video signal-to-noise ratio (snr) of 35 dB when the camera is viewing a scene containing a highlight of 1.0 foot-lamberts. The snr is defined as the ratio of peak-to-peak signal to rms noise within a 2 MHz bandwidth. For purposes of this measurement, the rms noise may be considered as 1/6 of the peak-to-peak noise. The observation/measurement of noise may exclude any coherent noise in the signal. Aperture compensation required to meet any of the following performance specifications shall be operative for confirming measurements of this and the following performance elements.

3.4.2 Operating Light Range. The camera must be capable of operating over a total scene highlight brightness range of 1.0 to 10,000 foot-lamberts. The snr shall be at least 35 dB over this range.

3.4.3 Automatic Light Control (ALC). ALC circuitry shall be incorporated to permit operation over a 1000:1 range of scene illumination. When operative, the circuitry will function on average scene brightness or in a peak mode (5 percent, or more, field-of-view for peak scene brightness).

3.4.4 Iris Range. The operating range of the iris shall provide a light range of 900:1. A range of f/2.2 to f/66 may be considered typical.

3.4.5 Dynamic Range. With the ALC in peak mode and the camera viewing a static scene, the camera shall be capable of providing an output signal, black-to-white, which encompasses a 32-to-1 range of scene brightness (11 EIA logarithmic shades of gray).

3.4.6 Signal-to-Noise Ratio (SNR)

3.4.6.1 Non-Coherent Noise. The output snr shall be at least 35 dB for a 2 MHz bandwidth over the operating light range, exclusive of any coherent noise components in the signal.

3.4.6.2 Coherent Noise. The ratio of peak-to-peak output signal to peak-to-peak coherent noise in a 2 MHz bandwidth shall be at least 1000. (Compliance may be considered adequate if the noise is not perceptible in a normally adjusted monitor picture.)

3.4.7 Resolution

3.4.7.1 Center Resolution. The horizontal resolution shall be at least 80 percent at 200 TV lines. (The central vertical stripes on a RETMA chart may be used for the measurement.) Limiting resolution as viewed on a monitor display of a RETMA chart shall be 350 TV lines per picture height for the center horizontal and vertical wedges.

3.4.7.2 Edge Resolution. Numerical values shall be 80 percent of the requirements for center resolution. Response at 200 TV lines on the corner wedges shall be 65% and limiting resolution shall be 280 lines per picture height.

3.4.8 Geometric Distortion. The displacement of any element in a center, 80% ellipse, shall be no more than 3% of picture height, and no more than 5% for the remaining area. (A design objective shall be less than 2% distortion for the entire raster).

3.4.9 Shading. Black or white shading shall not exceed 10% within the 80% ellipse and shall not exceed 20% for the remainder of the raster. Shading is defined as a percentage of the video signal in the center of the picture for a 300 nanoampere output excursion. The measurement may be made neglecting, or subtracting, the effects of lens produced shading components.

3.4.10 Power Consumption. The TV camera shall require no more than 15 watts for operation at +28 volts.

3.5 Environmental

3.5.1 Temperature. Environmental temperature conditions are not specified. It is assumed, however, that an extreme temperature range may be encountered and that heaters and/or coolers may be required to maintain a safe operating temperature range.

3.5.2 Operating Pressure. It must be assumed, for camera design and modularization, that for some remote operations, critical pressure will be experienced. Potting materials and interconnection should be designed for operation in any environmental pressure. Approximately normal atmospheric gas content should be assumed.

3.5.3 Vibration, Shock and Acceleration. Vibration, shock, and acceleration should tentatively be based on worst case Apollo-camera test values, see RCA Dwg. No. PS-2260580.

3.5.4 Sun Exposure. Inadvertent imaging of the sun may occur. The camera performance should recover within one minute following a maximum 30 seconds exposure to the sun, and undegraded performance should then be available.

4. PAN/TILT UNIT

4.1 General. The pan/tilt unit is a remotely controlled azimuth/elevation mount for the TV camera that permits control of camera pointing angle from a remote location. The pan/tilt unit electronics will receive power via the command decode circuitry in the TV camera. The camera will also provide decoded azimuth and elevation signals to the pan/tilt unit.

4.2 Physical Requirements

4.2.1 Mechanical. The form factor of the pan/tilt unit may depend on the available spacecraft volume. A realistic maximum volume of 960 cubic inches is specified as being representative of a typical installation for a form factor of 12-by-10-by-8 inches. The unit weight shall not exceed 10 pounds.

While in orbit maintenance or replacement of a TV camera is not a planned operation, the camera-to-pan/tilt unit interface shall be of simplified design to permit emergency replacement. The camera attachment mechanism shall permit replacement with no more than a single special purpose tool.

4.3 Functional Requirements

4.3.1 Coverage. The pan/tilt unit will be capable of travel adequate to permit camera pointing which will encompass the complete volume for the planned operation or experiment. Limit switches will be employed to restrict the travel to the desired range of elevation and azimuth.

4.3.2 Rates. The typical remote operation will require variable rate operation of the pan/tilt unit. This function may be met with a continuously variable or a series of discrete step rate increments. A range of 5-to-1 in rates is required.

4.3.3 Interference. The pan/tilt unit shall generate no radiated or conducted interference that will be visible in the TV picture.

4.3.4 Drive Quality. Motion shall be smooth and free from apparent jerkiness as judged by viewing a TV monitor during system test.

4.4 Performance

4.4.1 Azimuth Range. In response to pan signals with the limit switches adjusted for maximum range, the azimuth angle will be adjustable to $\pm 170°$ from the nominal center (zero) position.

4.4.2 Elevation Range. In response to tilt signals with the limit switches adjusted for maximum range, the elevation angle will be adjustable from 60 degrees below-to-90 degrees above the horizontal (zero) position.

4.4.3 Rates. Rates of motion for both pan and tilt shall encompass a range of from 2-to-10 degrees per second. If discrete increments are employed to obtain this range, nominal rates shall be 2, 3, 4.5, 6.7, and 10 degrees per second.

4.4.4 Power. The pan/tilt unit shall consume no more than 10 watts when the motors are stationary. An additional 5 watts, maximum, may be consumed for a motor drive when a pointing adjustment is being made.

4.5 Environmental. The conditions specified in Paragraph 3.5 are applicable to the pan/tilt unit.

5. TV MONITOR

5.1 General. The TV monitor is the functional unit providing the visual display of the remote operation to the monitor. As such it provides the visual interface between the operator and the scene. Therefore, primary emphasis must be given to observer field-of-view, brightness and contrast range. It is assumed for the following paragraphs that the observer viewing distance is in the range of 15-to-30 inches, with a 20 inch nominal distance, and that surround illumination is low, or controllable to a maximum of 25 percent of monitor brightness.

5.2 Physical Requirements

5.2.1 Mechanical. The weight of the TV monitor shall not exceed 15 pounds. The form factor of the monitor will be approximately rectangular in the horizontal and vertical planes and will be contained within a volume of 8-by-8-by-13 inches (width-by-height-by-depth).

5.2.2 Electrical. The monitor will employ an eight inch diagonal, rectangular kinescope with P4 phosphor. The nominal picture format will be 4.8-by-6.4 inches. Normal operation of the monitor will be obtained with a power source of 28 volts, ±10 percent.

5.3 Functional Requirements

5.3.1 Synchronization. The monitor must be capable of precise lock to the synchronization signal. Two switchable operational modes are required. The primary mode will employ a separate 75 ohm coax feed line carrying a composite sync signal to permit monitor phase and frequency lock to the TV signal. The alternate mode requires stripping of the sync signal from the composite video line to effect the same result.

5.3.2 Controls. In addition to the sync mode selector described above, operator accessible controls will include brightness, contrast, and power.

5.3.3 Video. The monitor will be designed to receive the video signal from a 75 ohm coaxial line. The monitor shall provide a 75 ohm termination to the video line. Normal video level on the terminated line is 140 IRE units of composite signal.

5.4 Performance

5.4.1 Brightness. The monitor with implosion shield and any external front surface filter shall provide a highlight brightness of no less than 100 foot-lamberts, termed reference brightness. The brightness level control shall provide an adjustment range of no less than 20-to-1.

5.4.2 Contrast Ratio. The monitor shall provide a contrast ratio of 10-to-1, minimum, at reference highlight brightness with an incident surround light level of 25 foot-candles. The contrast control shall have a minimum range of 20-to-1. At reference highlight, with low surround lighting, the monitor shall be capable of displaying a contrast ratio of 50-to-1 minimum.

5.4.3 Resolution. The horizontal MTF, without aperture compensation, shall be a minimum of 0.8 at a packing density of 75 TV lines per inch. Vertical resolution shall be the same as horizontal (circular spot cross section) except as modified by the scan line process.

5.4.4 Picture Quality. No low frequency streaking shall be observable for a 100 percent video step. Ringing, undershoot or overshoot, shall not be discernible at transitions equivalent to full amplitude at the system resolution of 360 TV lines per picture height. With a blank raster spurious background patterns shall be less than 0.05 of reference brightness.

5.4.5 Geometry. Non-linearities in horizontal or vertical directions shall be less than 2 percent of the format.

5.4.6 Video Channel. In addition to the requirements imposed by the previous performance paragraphs, the video channel shall be flat to within 1 dB up to 5 megahertz at any control setting and shall be capable of full kinescope drive at 30 percent video level.

5.5 Environmental

5.5.1 Temperature. The monitor shall operate within specification for an ambient of from 0-to-50 degrees Centigrade.

5.5.2 Operating Pressures. The monitor is intended for operation in a nominal pressure environment. However, exposure to vacuum for extended periods shall not result in degradation. Compliance may be demonstrated by 12 hours exposure at vacuum/temperature extremes of -10 and +60 degrees Centigrade.

5.5.3 Vibration, Shock, and Acceleration. Paragraph 3.5.3 shall apply.

6. CONTROL UNIT

6.1 General. The control unit is the functional segment of the TV system that enables operator control of the TV cameras, generates signals for routing of video information, and master synchronization of the system. Together with a companion processing unit, which it is assumed will share a mounting location, it provides all of the remaining electrical functions not contained in the cameras and monitors.

6.2 Physical Requirements

6.2.1 Mechanical. The control unit will consist of two parts, a control panel and control electronics which may be physically separated. The control panel will contain the switches and potentiometers necessary to provide control information while the control electronics will interpret, format, and encode the information.

The control panel will be contained in a volume of 300 cubic inches or less, consisting of a depth of no more than 2.5 inches and panel dimensions of approximately 10-by-12 inches. Weight shall not exceed 2 pounds.

The control electronics will be contained in a package weighing no more than 6 pounds. The volume of the package will occupy a maximum of 300 cubic inches in a form factor such as 6-by-8-by-6 inches.

6.2.2 Electrical. Normal operation of the control unit will be obtained with a 28 volt, ±10 percent, power source. Power consumption will not exceed 8 watts.

6.3 Functional Requirements

6.3.1 Controls and Commands. Signals generated by activation of controls shall be divided into classes: (1) those signals causing an electronic switch to be activated and thereby affect a video routing or processing change in the processor unit, and (2) those signals which control or activate the TV cameras and their associated pan/tilt units. In the second category, with the exception of the camera power (ON/OFF), all signals will be multiplexed in a format suitable for transmission over a single 75 ohm video line and for efficient decoding at the TV camera locations.

6.3.1.1 Power. An individual toggle switch will be employed for each camera to apply or remove power. Power application will be effected by activating a latching relay to complete the power feed circuit to a particular camera.

6.3.1.2 Video Select. A separate video select pushbutton or switch closure, shall be provided to enable selection and routing of each video signal for feed to either monitor, to a particular transmitter for earth or other satellite feed, to a particular on-board video tape recorder, or any other as yet undefined equipment segment requiring video information. All video switching shall be accomplished during the vertical blanking interval.

6.3.1.3 Gamma Correction. The gamma correction control shall modify the transfer characteristic of the video amplifier(s) in the Processor. The range shall extend from a minimum of at least 0.5 to unity (no correction), and is either continuously variable or will have a minimum of three positions: 0.5, 0.7 and 1.0.

6.3.1.4 Camera Identification. A camera identification, assigned to each camera, will be selected via a control panel switch. The camera identification number will serve to activate a particular camera decode system to enable processing of commands addressed to that camera.

6.3.1.5 Automatic Light Control (ALC). A three position switch is required to generate the multiplexed command. The command will be issued at least twice and then be inoperative until a change is initiated. After decoding, a latching relay arrangement will establish the appropriate ALC mode: (1) peak, (2) average, or (3) out. Reissuance of the same command will not alter the operation of the camera unless a new mode is ordered.

6.3.1.6 Focus. Two commands are required, one to focus the camera lens closer and the other to focus farther. The control will be via a single, return-to-neutral, lever type switch. The command will be encoded and multiplexed with any other simultaneously issued commands and executed at the camera subsequent to decoding.

6.3.1.7 Iris. Two commands are required to open or close the iris. Paragraph 6.2.1.6 is otherwise operative.

6.3.1.8 Zoom. Two variable rate commands are required, one to shorten and the other to lengthen the lens focal length. Coding for a minimum of 5 rates is required and activation via a joystick control is preferred.

6.3.1.9 Azimuth and Elevation. A single joystick control will be employed to effect variable rate positioning of pan/tilt. The amount of joystick deflection, horizontally and vertically will generate information to be encoded and establish the rate of adjustment. The information will be decoded at the camera location and fed to the associated pan/tilt unit for execution.

6.3.2 Synchronization. The master sync generator is located in the control unit. The composite synchronization information, horizontal and vertical, will be compatible with the requirements of Paragraph 3.3.1. The sync generator output will be time division multiplexed with the command information, with command intervals limited to normal active video time, and routed to each camera via a 75 ohm coaxial line.

6.3.3. Levels. The sync and command information will be combined to provide a normal amplitude composite signal of 140 IRE units. The sync amplitude will have the same 40 units as for the normal video lines (Paragraph 3.3.2.4) with the command information contained in the usual 100 units normally containing video.

6.4 Environmental. Paragraph 5.5 shall apply.

7. PROCESSOR

7.1 General. The Processor is the functional segment of the TV System that compensates for loss in video lines, switches and routes signals, provides controllable levels of gamma correction, and provides buffer amplification of the video signals for distribution to other locations. Together with the companion Control Unit it provides all of the electrical functions not contained within the cameras and monitors.

7.2 Physical Requirements

7.2.1 Mechanical. The Processor will consist of an electronics box with connectors for power feed and incoming control/command and video signals, and outgoing video signals. The box will be nominally rectangular in cross-section and have a volume of 250 cubic inches, or less, in a form factor such as 6-by-8-by-5.2 inches. The weight of the box shall not exceed 5 pounds.

7.2.2 Electrical. Normal operation of the Processor will be obtained with a 28 volt, ±10 percent, power source. Power consumption will not exceed 6 watts.

7.3 Functional Requirements

7.3.1 Line Equalization. Termination of each video line (signal) at the processor input shall be provided. Buffer amplification and signal equalization shall be incorporated to normalize the signal amplitude and compensate for any frequency dependent roll-off.

7.3.2 Switching. Switching of any video line shall be accomplished in response to a select signal fed from the Control Unit. Switching capability shall permit routing of each video signal to either monitor, to an associated tape recorder, to any operational transmitters, or any undefined equipment segment requiring video information. Interruption and re-routing of a video signal shall take place during the vertical blanking interval.

7.3.3 Gamma Correction. The transfer characteristic (gamma) of the video amplifier shall be adjustable in response to operator initiated adjustments. The correction circuitry shall also function to maintain constant amplitude for a video signal extending from black-to-peak white.

7.3.4 Distribution Amplifiers. Buffer amplifiers shall be included in the Processor, for each output video line. These amplifiers shall provide 75 ohms sending end impedances for each output signal to be distributed external to the Processor. Each amplifier shall be designed so that a short on one, or more, of the lines shall not affect the remaining amplifiers.

7.4 Performance.

7.4.1 Frequency Response. The frequency response from a camera output (input to the camera coax line) to the output of the processor shall be flat within ±0.5 dB to 3.5 MHz and ±1.0 dB to 5 MHz. Measurements shall normally be made with the gamma control set to unity.

7.4.2 Waveform Distortion. Waveform testing and bar (half line and half field) shall be used to establish waveform response from the camera output to the Processor output. Measurements with a 2T pulse shall result in an amplitude difference no larger than 1 percent of the half line pulse. Distortion of the half line bar shall similarly not exceed 1%, overshoot or undershoot, of nominal amplitude.

Distortion of the half field bar shall be no greater than 2 percent. That is flatness shall be adequate to maintain amplitude at leading or trailing edge of the bar to within 2 percent of the center-of-bar value.

7.4.3 Gain. The nominal low frequency gain of the video channel shall be unity, $\pm$0.5 dB, as measured from the camera output to the Processor output. This response shall include the coax cable, line equalizer, gamma, and distribution amplifier elements of the channel. Measurements shall be made with a composite signal containing a full black-to-white transition. Gain shall be maintained for any value of gamma from unity to the lower limit.

7.4.4 Signal-to-Noise Ratio. The signal-to-noise ratio of the video channel (camera output to Processor output) shall be no less than 50 dB, peak-to-peak signal-to-rms noise. Gamma shall be set to unity for this measurement.